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Critical path

The recently energized East China/Jiangsu 500 kV transmission project employs the world's tallest transmission towers, reaching 346.5m at the Yangtze River crossing. The $50.7m project was completed under challenging conditions, and has relieved a major bottleneck in the East China grid.

The East China/Jiangsu 500 kV power transmission project is being implemented against the background of the rapidly rising demand for electric power in Jiangsu province, China. The overall project objective is to alleviate critical bottlenecks in power transmission in east China and to promote electricity trading on a commercial basis, so providing a prerequisite for economic growth by making available sufficient power to consumers. This goal is considered to be attainable most economically through expansion of the existing 500 kV power system.

New high capacity power plants are to be built along the seashore of north Jiangsu province, but this electricity has to be supplied to the load center of south Jiangsu, which is separated by the Yangtze River. So, an important component of system expansion is a crossing of this river by the 500 kV double circuit overhead line of 2000 MVA capacity per circuit, running from Yangdong to Doushan. Project planning started in 1998 and foundation construction commenced in 2001. The overhead line was first energized on 18 November 2004.

The crossing is located between the cities of Nanjing and Shanghai, 200 km upstream of the Yangtze River estuary. Both sides of the river are embanked and the terrain is totally flat. At this point, the river is more than 2 km wide and heavily populated on both sides, with the land used intensively for agriculture and industry. To optimize the right of way, some dwelling houses had to be pulled down and families resettled. New modern houses were erected for them near their original location.

The Yangtze River is a major transportation waterway, and is used by ocean-going vessels at this section. The highest water level has been established as 5 m above sea level, and then clearance of 50 m for the highest ships plus 6 m electrical safety clearance to the lowest conductor must be assured.

Figure 1. Constructors step carefully as they work on building the world's tallest transmission tower

Suspension towers

The tower is equipped with two 500 kV circuits in a 'Danube' configuration, plus one groundwire and one optical ground wire (OPGW). The span between the two suspension towers is 2303 m. Considering a ground level of 4 m below highest water level, total clearance to the lowest conductors of 56 m, a conductor sag of 227 m, an insulator string length of 10 m and a tolerance of 5 m, a height of 302 m is obtained for the bottom suspension string attachment point. The total tower height is calculated by adding the vertical distance to the upper conductor crossarm of 27 m and the distance to the groundwire crossarm of 17.5 m, for a height of 346.5 m. The maximum crossarm length is 38.5 m from the tower axis; the tower width at the top totals 8 m but at ground level it is 68 m. One tower weighs 4192 t.

The towers are lattice steel structures of welded and rolled angle profiles. During the preliminary design stage, a comparison was made between angle steel towers, tubular steel towers and reinforced concrete towers. Although all options can boast successful experience in design, fabrication and operation, the angle steel tower possesses some advantages: a high degree of production automation; machining quality is easier to guarantee; no inner concealed surfaces; galvanization quality is easier to check; no vibration problems under gentle breezes; and better fatigue resistance and lower costs than reinforced concrete towers.

The Jiangyin Yangtze river crossing now has the highest transmission line towers in the world. Previous towers with a height of above 200 m are mostly located in China and Japan.

The tower top geometry is determined by the electrical safety clearances at the tower and at midspan under normal (no wind) and exceptional (maximum wind or galloping conductor) conditions. Under Chinese regulations, the horizontal distance between conductors in long spans has to be 22.5 m. This value corresponds with the Norwegian rule for fjord crossings of one per cent of maximum span. The distance to the tower is fixed by the swing-out behaviour of the insulator string and the allowable air gap. Determination of the vertical distance between conductors takes account of conductor

Table 1. Highest transmission line towers of the world

Project Name	Country	Volt (kV)	Span (m)	Circuits	Conductors (per bundle)	Tower height (m)	Tower type	Year of completion
Jiangyin Yangtze River Crossing	China	500	2303	2	4	346.5	Lattice box angle steel	2004
Nanjing Yangtze River Crossing	China	500	2053	2	4	257	Reinforced concrete	1992
Orinoco River Crossing	Venezuela	230	2537 + 2161	2	1	240	Lattice box angle steel	
Zhujiang Crossing	China	500	1547 + 931	2	2	235.75	Lattice box angle steel	1990
Wuhu Yangtze River Crossing	China	±500	1910	2	4	229	Tubular tower	2003
Elbe River Crossing	Germany	380	1200	4	4	227	Lattice box angle steel	1978
Chusi Crossing	Japan	220	2357	2	1	226	Tubular tower	
Daqi Channel Crossing	Japan	220	2145	2	1	223	Tubular tower	1997
Suez Canal Crossing	Egypt	500	600	2	4	221	Lattice box angle steel	1998
LingBei Channel Crossing	Japan	500	1463	2	4	214.5	Tubular tower	1993
Luohe Crossing	China	500	1478	2	4	202.5	Reinforced concrete	1989

galloping (ellipse axes of 8 m horizontally and 16 m vertically), recoil when ice falls off and electrical clearances. This was calculated to 27 m. The vertical distance between groundwire and conductor is selected as 15 m, and depends on the lightning protection angle at midspan, ice drop-off recoil distance and galloping.

Anchor towers

For each circuit, two anchor towers take up the conductor tension forces left and right of the river crossing. The span in each case between suspension and anchor towers is 700 m. These towers are of rectangular cross-section of dimensions 16 m x 24 m at ground level. Each of the four anchor towers has a height of 55 m and weighs 110 t. A cruciform component composed of two heavy angle steel sections welded back-to-back is the main member of the tower body below the crossarms. A maximum leg pressure of 4058 kN and a maximum leg uplift of 3848 kN have to be transferred to the foundations. The crossarm axis is perpendicular to the crossing span, and the distance between the two towers on each side is 40 m.

Conductors and groundwires

The crossing ensures power transmission at 2 x 2000 MVA, or 3200 MVA if just one circuit is in operation. The conductor has to transmit the corresponding current under conditions of 40°C ambient temperature and 0.6 m/s wind speed. But the conductor's mechanical strength is decisive for the design and cost of the crossing. Only aluminium alloy conductors with high tensile steel reinforcement are able to combine high conductivity with an adequate tension-weight ratio for economic sags. The design process included a review of the conductors used in existing crossings, investigations of new types with closed surfaces, electric field calculations, and comparisons between different bundle configurations. Finally, a quadruple bundle of conductor type AACSR 500 (42/3.9 aluminium alloy, 19/3.9 high tensile steel) was chosen.

The operating stress in the conductor affects not only sag and tower height but also conductor safety and susceptibility to vibration. Conductors of existing crossings are designed for everyday stresses (EDS) in a range of between 17 per cent and 25 per cent of the conductor's ultimate strength. The relationship between EDS and sag can be illustrated for the conditions of the Yangtze Crossing: a reduction in


Figure 2. The Jiangyin Yangtze River crossing spans 2303 m strung between towers standing 346.5 m high.

Table 2. Meteorological conditions

	Air temperature [°C]	Wind speed [m/s]	Ice thickness [mm]
Minimum	-15	-	-
Maximum	40	-	-
Every day	15	-	-
Highest wind	15	32	-
Ice covering	-5	10	10
Erection / maintenance	0	10	-

EDS of one per cent results in a sag increase of approximately 11 m. After consideration of all economic and technical factors, an EDS of 20.2 per cent was selected. The maximum conductor stress is restricted to 40 per cent under the conditions of combined ice and wind loading. The actual value calculated amounts to 36.2 per cent and corresponds to 724 kN per phase bundle. Additionally, a combination of ice and wind loading that occurs very rarely is considered, and the conductor stress limited to 60 per cent of the ultimate strength.

Normally the thermal limit during short-circuit currents decides groundwire design but for long span crossings only the mechanical strength is decisive. The mechanical behaviour has to match that of the phase conductor to ensure lightning protection under all conditions. If the tension-weight ratio of the groundwire is higher than that of the conductor, the top part of the tower can be reduced in height. Good corrosion resistance is also required. The investigations resulted in a groundwire of aluminium-clad steel, ACS 360 (37/3.5), with a tension-weight ratio of 17.9 > 15.2 (AACSR 500) and a maximum short circuit current capacity of 400 kA^2s.

Figure 3. The towers were constructed in 135 work days spread over 17 months

Components of strings

Considering the long span length, the weight of the quadruple conductor, wind, and ice loading conditions with a safety factor of 3.0 for all loads including the maximum conductor tension, the minimum failing load of the insulator sets is 2120 kN for the suspension set and 2400 kN for the tension set. The suspension string consists of four sub-strings, each of 33 cap-and-pin type porcelain insulators. The tension set has six sub-strings, each of 26 cap-and-pin type porcelain insulators. Total creepage paths are calculated as 19 800 mm and 13 650 mm for the suspension and tension strings, respectively.

Table 3. Clearances at tower

	Wind speed [m/s]	Swing-out angle [°]	Minimum clearance [m]
Operating conditions	32	31	1.2
Switching conditions	16	11	2.5
Lightning conditions	10	6	5.6

In view of the crossing's unusually extreme conditions, special accessories and fittings were developed and passed all tests to confirm the theoretical calculations. Suspension type clamps are adapted to cater for special deflection and outlet angles, so that no non-allowable conductor stresses will arise. The clamps can also withstand unbalanced longitudinal conductor forces. The saddle clamp is 1.55 m long, weighs 116 kg and has 2.54 m long armour rods that are fitted on the conductors before installation. For conductor anchoring, compression-type tension clamps are used, which have been tested to withstand 95 per cent of the ultimate conductor strength (475 kN).

Suspension design

Twenty different loading cases are considered for the structural analysis of the tower, including normal and rare extreme wind conditions, normal ice covering combined with wind, rare extreme ice covering, broken conductors, conditions during stringing of conductors and groundwires, and tower erection loads. All loads are calculated according to the limit process based on probability statistics. During normal wind conditions, the reference wind speed (v_0) is assumed as 32 m/s at a height of 10 m, and the ground roughness is fixed as B class in accordance with China's official specification for architectural structural loading. The wind speed coefficient depends on height and is calculated from 1.0 x $(z/10)^{0.16}$, where z is the height above ground. The wind acts at angles of 90°, 60°, 45° and 0° to the line axis. For the rare wind condition, the reference wind speed is assumed as 35 m/s acting at an angle of 90°. The Eiffel effect as a function of tower slope variation according to BS 8100, wind loading on the towers without conductors before stringing as well as all loads regarding conductor galloping are considered.

Normal ice covering conditions comprise an ice thickness on the conductors of 10 mm and a wind speed of 10 m/s. The rare ice condition assumes an ice thickness on conductors and groundwires of 20 mm and 25 mm, respectively, while wind speed is 15 m/s.

The contract for crossing tower manufacture was awarded to a joint venture of Balfour Beatty and Cleveland in December 2001, following international competitive tendering in line with the procurement guidelines of the World Bank.

Due to the unique tower structure, the manufacturer was faced with major challenges: welding of cruciform profiles of 40-65 mm thickness, welding and galvanization of high strength steel components of 12 m length and 2 m width, and design of special structure junction points with compact plate configurations of 60-100 mm thickness and 18 t weight. To check that quality requirements could be met, a cruciform prototype was manufactured and tested before series production. The experience gained from this showed that it would be better to define prototypes for special member junction points, too.

Member forces

The loading conditions decisive for member rating are normal wind conditions, rare ice covering and broken wire conditions. The maximum leg compression force amounts to

71 057 kN and the maximum leg uplift force 52 642 kN.

A square-section, bolted lattice box member with a side length of between 800-1200 mm is used as the main member in the middle and bottom sections of the crossing tower. This is built up of four welded cruciform components with a maximum thickness of 65 mm and angle bracing bars. A lattice component composed of four pieces of heavy angle steel is used as the main bracing of the tower body. A double baseplate is used at the tower bottom to prevent laminated tearing due to the extremely high internal forces.

At a height of 120 m, the structure is quite complicated because the tower body changes its slope angle at the junction point. The thickness and section dimensions of the lattice box members above and below this junction are different. To ensure the necessary stress transmission at the junction, a welded block component built up of a central cross part with a thickness of 100 mm is inserted between the four cruciform members in the corners. Each node weighs approximately 18 t.

As the internal forces between the structural members are unusually high, normal stress analysis software could not be used. The East-China Electric Power Design Institute has developed two special programmes, Box and MSF, which may be linked to the 'Tower' programme – a finite element programme developed in Canada and adapted for calculating the static forces of the crossing tower – via an automatic interface. The Box programme is used mainly to design components with a lattice box-type section, while the MSF programme calculates components made up of single angle, double angle, butterfly and quadruple angle profile sections.

> *"The Yangtze River is the most important waterway in China. Therefore, stringing without closing the navigation channel was adopted for this project"*

Foundation

A technical and economic comparison between the options of pre-tensioned spun high-strength concrete (PHC) piles, steel pipe piles, H-type steel piles and filling piles was carried out in the initial stage of foundation design. The investigations resulted in the choice of PHC piles, and tests of mechanical strength under field conditions showed a 7200 kN compression bearing capacity and 2300 kN uplift capacity.

Table 4. Soil conditions

Depth (m)	Soil type
0-11	Silty sand
11-20	Fine sand
20-27	Embedded layers of silty clay and silty sand
27-37	Silty clay
37-44	Silty sand
44-56	Fine sand

The design of the foundation comprises 56 PHC piles under every leg of the crossing tower with a pile length of 38 m and a pile spacing of 2.5 m. The foundation cap is positioned diagonally with a length of 19.5 m and a width of 17 m. Tie beams are laid out between every two caps of the foundation and designed with a cross section of 2 m x 1.6 m. Two bearing piles of 25 m length support the tie beam.

A recess equipped with anchor bolts was provided at the foundation top to install the double base plate of the tower and to prevent its movement under the action of the design loads. The base plate was inserted into the recess. After adjustment of the leg, the bolts were tightened and the recess filled with grout. The depth of embedment of the base plate into the foundation is 1350 mm. The anchor bolts are of 42CrMo high-tensile alloy structural steel, ensuring strength and elasticity.

Table 5. Maximum foundation loads

	Compression (kN)	Uplift (kN)
Axial load	-71 890	+53 780
Horizontal load x-direction	12 010	9 065
Horizontal load y-direction	11 930	8 982

Foundation settlement has been continuously monitored since starting concrete pouring and installation of conductors and groundwires. Up to now, settlement of the four foundations of the tower is absolutely consistent, totalling 6 mm.

Welding of cruciform profiles

The lattice box member structure of the suspension tower consists of four welded cruciform sections made of 25 mm to 65 mm thick high-strength steel plates.

Welding was done to the international standard ANSI/AWS D1.1, and procedures and tests were adapted to suit. During fabrication, non-destructive examination was effective in locating hidden faults in weld seams. Steel plates exceeding 40 mm were tested 100 per cent by ultrasonic inspection and 20 per cent by magnetic particle inspection. To clear up any remaining doubts concerning the test results, radiographic inspection was applied to clarify the nature of any faults. If cracks were detected in the weld surface, additional dye penetration inspections were conducted.

During a routine pre-assembly test of 286 m junction points and the mid-tower sections (206-286 m), penetration cracks were detected in the welding seams and adjacent steel plates. The overall inspection revealed some shortcomings in the fabrication process. Finally, the supplier agreed to re-manufacture these structural components. In order to simplify the manufacture and to minimize the project delay, it was agreed to revise the design and apply the welded cruciform sections made with steel plates instead of the large rolled angle sections.

Size induced problems

Technical and quality problems arose during fabrication of the junction point at 120 m. This is located where the tower body changes its slope and the size of the box member changes from 1200 mm to 800 mm. It is welded from 65/100 mm and 60/100 mm high strength steel plates, and is very complex and difficult due to space constraints with insufficient access between the plates. The fabrication process was improved by changing the preheating and interpass temperatures, closer supervision, and heat treatment of the complete junction point after manufacture. Finally, full penetration welds could be performed and deformations avoided.

Timetable

Erection of the crossing towers took 17 months, starting on 8 November 2002 and finishing on 13 April 2004, with both crossing towers erected in parallel. Work was stopped four times due to delays in delivering main components with the longest interruption from 17 July 2003 to 7 February 2004. Erection was influenced by bad weather for 76 days, mainly in the first half of 2003 and spring of 2004. Due to rainy and foggy weather, erection and stringing work could not proceed continuously, so making it difficult to schedule the jobs on site. Fortunately, this had no serious consequences. Ultimately, the effective construction period was 135 days with a working rate of 14 t every day.

The Yangtze River is the most important waterway in China, with average traffic on the river exceeding 2500 ships per day at the crossing location. Therefore, stringing without closing the navigation channel was adopted for this project. Stringing started on 14 May 2004 when the helicopter strung the first pilot wire. Eighty days later the process was complete. In total, twenty-four conductors, one groundwire and one OPGW with all fittings were installed.