The Sutong Bridge across the lower Yangtze River in China will have, when completed, the longest span (1,088 m) and the highest towers (306 m) of any cable stayed span in the world. The foundations for this record setting span will also be record setting. They are located in water depths exceeding 30 m with maximum flows exceeding 3 m/sec. The soil at the site of the main pylons consists of layers of silty sands and silty clays extending to bed rock at 270 m below river elevation. This paper describes the innovative methods used by the team of foundation designers and constructors to support this record setting bridge at this very challenging site. This paper covers three specific topics related to the foundations of the Sutong Bridge:

- Design and construction of the 131 drilled shaft (2.8/2.5 m diameter and 114/117 m long) under each of the two main pylons,
- Design and construction of the scour protection for the two main pylons,
- Construction methods used to construct the waterline pile caps (113.8 m by 48.1 m by 13.3 m deep) under each pylon.

Introduction

Detailed design of the Sutong bridge was performed by The Design Group of Sutong Project. Construction management of the entire project is being performed by the Jiangsu Provincial Sutong Bridge Construction Commanding Department (CCD). COWI A/S and Ben C. Gerwick, Inc. served as special consultants to CCD during design and construction of the bridge.

The width of the Yangtze River at the bridge site is approximately 6 km and the total length of the Sutong bridge is approximately 8 km. The site conditions for the main towers are extremely challenging. The northern pylon, Pier 4, is located in about 30 m water depth and the southern pylon, Pier 5, is located in about 16 m water depth. The river is subject to both high fresh water run off volumes and tidal effects, creating currents exceeding 3.0 m/sec in the extreme conditions. Maximum potential wave heights at the site exceed 3.5 m. The river is alluvial and subject to rapid changes in bottom contours due to high erosion and deposition rates. The river bed at the northern pylon consists of sandy materials and at the southern pylon, the bed material is mainly silty loam and silty clay. These site characteristics create a condition where the river bottom will immediately respond to the introduction of any structure such as a bridge pier or pylon. Hydraulic model studies for the bridge, performed by the Nanjing Hydraulic Research Institute, predicted up to 29 m of scour (100 year return period) at the south pylon with a caisson foundation and up to 24 m of scour (300 year return period) at the same location for a large diameter pile foundation solution (Jensen, 2004).

Bed rock is located at approximately 240 m below the river bottom. The soils in the upper 240 m consists of layered sediments of fine sand, course sand, silty sands and gravels with occasional layers of clay.

The river is the main waterway to the entire Yangtze Basin with heavy barge traffic and up to 50,000-t container ships in the main navigation channel.

Fig. 1   SUTONG BRIDGE – 1,088 m MAIN SPAN
Foundation Design

The foundation for each A-shaped pylon consists of 131 drilled shafts, 2.8/2.5 m in diameter. See Fig. 4 for layout of the pile cap and drilled shafts at each pylon. The drilled shafts are capped by a 13 m deep dumbbell-shaped pile cap with plan dimensions of 113.8 m by 48.1 m.

The bottom of the cap tremie seal is positioned at Elev. -10.0 m, approximately 12.0 m below mean sea level. The drill shaft casings are 2.8 m diameter with a wall thickness of 25 mm. See Fig. 5. The permanent casings extend from Elev. -7.0 to Elev. -53. The drilled shafts beyond the casing tip are 2.5 m diameter and extend to a design tip elevation of -124 at Pier 4 and -121 at Pier 5. Post grouting of the drill shaft tips was performed to increase the total ultimate capacity.

The ultimate load capacity of the drilled shafts was confirmed by four offshore load tests, two at Pier 5, the south pylon, and two at the approach piers. The two tests at Pier 5 confirmed an ultimate capacity of 92 MN (20,700 kips). Testing was performed using the Osterberg Cell Method. Test pile SZ5 was tested twice, before and after tip grouting, to give an indication of the increased capacity obtained through tip grouting. The tests indicated that the bearing capacity of the drilled shaft was increased by 20% or 15 MN (3,375 kips) by the tip grouting. The load deformation curve after grouting showed a much more rigid behavior than before grouting. This result demonstrated that the tip grouting had a positive effect on not only the tip but also on the side friction on the lower portion of the pile.

Drill Shaft Construction

Due to the high river currents, all drilled shaft construction was performed from a steel platform.
constructed over the top of the pier site. In addition, an upstream mooring platform (13 m by 44 m) and a downstream batch plant platform (39 m by 44 m) were constructed immediately adjacent to the main platform. See Fig. 6.

Fig. 6  BATCH PLANT PLATFORM

The top elevation of the drill platform was +7 m, approximately 3 m above high water. The main platform was used as both a template to drive the 131 drill shaft casings and to provide a work deck for the drill units. Casings at the northern pylon were driven to grade with a vibratory hammer and at the southern pylon a diesel hammer was used. See Fig. 7. After installation of each drilled shaft casing, bracing was added to tie each casing into the work deck, and thereby add rigidity to the entire work deck.

Fig. 7  CASING INSTALLATION HAMMER

Drilling was performed with 8 rotary-drill units position of the top of the work deck. Drill bits varied depending on the formations encountered. See Fig. 8 and Fig. 9. A bentonite slurry with a minimum positive head of 3 m was used to maintain drill hole stability. Both drilling and concreting operation were conducted simultaneously on the platforms. A minimum concrete strength of 5 MPa (725 psi) was required in an adjacent drilled shaft before drilling was allowed. The post tip grouting operation was also performed concurrently with these operations. However, the grouting operations maintained a minimum distance of 50 m from drilling and concrete placement operations in order to avoid hole-instability problems from elevated pore water pressure created by the grouting operation.

Fig. 8  2.5m DIA. DRILL BIT

Fig. 9  DRILL BIT EXITING HOLE

The reinforcing cages were fabricated in four sections and coupled together with threaded mechanical connectors on the work deck over the top of the casings prior to lowering them into the drill hole. Concrete was placed with a tremie pipe centered in the drill hole. See Fig. 10.
Concrete was supplied by a batch plant with a capacity of 100 cubic meters per hour, positioned on the downstream platform. Cement and aggregates were delivered to the platform by barges moored directly to the downstream platform.

Post grouting of the drilled shaft tips was performed with 4 loop-shaped pipes pre-attached to the reinforcing cage. The bottom of each loop turned at the bottom of the cage and extended into the interior of the drill shaft approximately 50 cm. Grout exited the pipes through 6 holes, 8 mm in diameter, drilled in the underside of each loop. A one-way valve was created by encasing the loop in a bicycle tire. To ensure that the system was not plugged during the concrete placement operation, clean water was pumped through the system under pressure to confirm open access to the surrounding tip area. Post grouting was performed with neat cement grout.

**Scour Protection**

The conceptual scour design for the two main piers was performed by COWI A/S, Denmark. The detail design was performed by Jiangsu Provincial Communication, Planning & Design Institute. Hydraulic studies and surveys were performed by Nanjing Hydraulic Research Institute.

The hydraulic design parameters for the scour protection were a combination of the current, water level and in some cases, waves acting at the same time. See Fig. 11.

The pile group width perpendicular to the river current is 48 m and the length is about 112 m. The hydraulic model tests showed the extension of the scour around the structure to be essentially equal in all four directions, approximately 60 m.

The ideas presented for scour protection were developed based on COWI’s experience in combination with their understanding of the very difficult conditions in Yangtze River with deep water, high currents and high sediment transport.

The major problem associated with the scour protection was its construction. The scour protection in itself had to be made in a way that it was not too difficult to construct, and also, that it would prevent scour during construction. It was assessed that if the bridge piers were made without prior scour protection, the development of scour will be so rapid that it would be difficult to construct the scour protection later on and the bed level would have eroded to such a low level, that the advantage of the existing bed levels would have disappeared.

Therefore the scour protection as presented in Fig. 12 was designed in such a way that it would allow for the construction of the piles through the central part of a temporary scour protection and then later on the final scour protection could be introduced.
It is further clear that due to the very high flow velocities and high sediment transport, the adopted scour protection scheme would need to be relatively simple and robust and not require very accurate dredging levels before placing of the material in the scour protection.

It was also desirable to construct the protection in smaller sections that together would constitute the total protection. The final protection should also be robust and be able to function with unavoidable inaccuracies.

Based on these considerations, the designers refrained from the use of large prefabricated mattresses, gabions or large bamboo/willow mattresses. Such solutions could be used but would be difficult to handle and place in the very high currents prevailing at the site.

The principal ideas for the scour protection of the pylons of the Sutong Bridge included the use of three distinct areas or zones.

(1) The Central Area or Inner Zone

This zone includes the central area where the bridge piles for the main pylons and temporary structures are present.

The area extends 20 m away from the structures. In this area, the river bed would be temporarily protected by use of layers (3 nos.) of sand-filled geotextile bags. See Fig. 13.

Fig. 12  SCOUR PROTECTION PLAN

Fig. 13  FILLING GEOTEXTILE BAGS

The idea behind this concept is that by this action, the river bed will be protected but it will still be possible to bore the piles through the protection. After completion of the piling, the final protection was constructed with a filter layer of quarry-run and minimum 2 layers of armour stones (rock).

(2) Outer Area

Beyond the inner zone, the Outer Area is situated. It extends about 40 m further out from the Central Area. The scour protection consists of one layer of sand bags covered with a layer of quarry-run on top of which was placed the same type of rock armour as for the central area.

(3) The Falling Apron Area

Outside the Central and Outer Area is the Falling Apron Area. Its width varies according to an estimate of the scour depth and the width was set at 1.5 times the actual maximum expected scour depth. The material in this area consists of quarry-run on top of which layers of quarry stones were dumped.

During construction of the Falling Apron Area, it was decided to dump a layer of sand bags at this area as well because extensive scour was occurring.
The concept of the falling apron has been used in many countries for river training structures where the scour is expected to reach to a level significantly below the level at which the structure is or can be built.

Table 1 shows the stone sizes of the scour protection for the North and South Pylon. The table also shows sizes of sand bags, which were exposed in the temporary protection during construction and were later on covered with stone material.

For practical considerations, the same size of bags were adopted all over and the same stone size for the outer area and falling apron. The actual sand bags used were of size: 1.6 m x 1.6 m x 0.6 m.

Extensive surveys were performed during construction using multi-beam echo sounder in order to control and verify the amount of materials dumped. The dumping of material was performed using a grid with 28 x 26 cells for the North Pylon and 16 x 16 cells for the South Pylon.

With respect to the armor stones, it was essential that the structural integrity be obtained. Therefore, it was crucial that 2 layers of armor stones are present in all areas. In layer thickness, this corresponds to 1.0 m for the Central Area and the Outer Area. For the inner section of the Falling Apron Area, it corresponds to 1.2 m thickness.

The scour protection is a flexible structure that will be subject to some displacement of material. Especially the Falling Apron will be moving during launching when scour occurs at its edges. Therefore a detailed monitoring program was prepared covering the entire bridge alignment.

The solution adopted, with sand bags and stone layers dumped from the water surface, was found to be the most feasible under the given difficult circumstances with water depth up to 30 m, high currents and zero visibility. The future erosion at the edges of the protection will be prevented from progressing close to the bridge piers by the use of the Falling Apron concept for the outer edge of the scour protection.

See Fig. A-6 and A-7 in the Appendix for further details of the scour protection system.

### Pile Cap Construction

The 13.3 m deep pile cap for each pylon is positioned at the water line with the bottom at Elev. -7.0 m and the top at + 6.3 m. The caps were constructed by first building a double-walled steel caisson-in-the-wet, directly above final location. The 1.8/2.0 m thick double wall or perimeter wall was constructed as a watertight compartment and served four basic functions. See Fig. 14.

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<th>Item</th>
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<td>0.60</td>
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</tr>
</tbody>
</table>

Table 1 Stone and Sand Bag Sizes for the Scour Protection Material at the North and South Pylon

The principle is that the material in the falling apron will launch itself down the scoured slope that will thereby stabilize itself.

See Fig. A-6 and A-7 in the Appendix for further details of the scour protection system.
It first served as the perimeter stiffening frame that gave the caisson its rigidity during lowering operations. Secondly it served as the buoyancy tanks to minimize the deadweight of the caisson as it was lowered into the water and down to final grade at Elev. -10.0 m. Third, it served as a temporary cofferdam and exterior permanent form for the casting of the pile cap. And finally, the perimeter wall acted as a permanent ship-impact protection fender during the service life of the bridge. The perimeter wall was filled with concrete below Elev. – 1.0 m.

The first caisson (North Pylon) when initially constructed was 118 m by 52.4 m in plan, 7 m high, and weighed approximately 3050 tonnes. See Appendix Fig. A-3. The bottom of the caisson was a steel plate stiffened by steel trusses that spanned the full width of the caisson and tied into the perimeter walls. The bottom deck of the caisson started out at approximately Elev. +6.0 and was lowered in three basic stages to Elev. -10.0. The first stage lowered the caisson approximately 5 m, at which point the caisson was floating under its own buoyancy. At the end of this stage, the lowering was stopped and the perimeter walls were increased to a height of 18 m and the lowering was completed in two stages to final grade by partial flooding of the cofferdam.

The lowering operation was performed with 16 strand jacks, DL-S418 (See Fig. 16.) supplied and operated by Dorman Long Technology, Ltd. For the layout of strand jacks see Appendix Fig. A-4.

All 16 jacks were spaced along the perimeter wall of the caisson and sat on support frames positioned over the top of the exterior drill shaft casings. Each jack had a safe working load of 418 tonnes, thus providing a safety factor of 2.2. The entire caisson was quite stiff and relative movements of only 10 mm between adjacent jacking points created a 35% differential loading. The entire lowering operation was controlled with a Dorman Long P40 computer control system which provided communications between jacks, power-pack and control computer. The lowering operation was performed with strokes of 200 mm and a stroke range of only 5 mm to ensure stable balanced loads between jacks.
Once the 13 m high caisson reached final grade at Elev. -10.0, the caisson was locked in position and the annulus between the drilled shaft casings and the steel plate of the caisson bottom deck was sealed. A 3.0 m deep tremie concrete seal was then placed over the entire bottom area of the caisson except for the 2 m wide exterior wall. After the tremie seal attained specified strength, the caisson was dewatered (See Fig. 18) and the rest of the pile cap was constructed in the dry. See Fig. 19.

For the second caisson (South Pylon), the entire caisson was assembled full height and weighed approximately 5,800 tonnes. This caisson was lowered by a strand jacking system from Tonji University to a self-floating condition, and final grade was reached by partial flooding of the exterior perimeter walls. Once at final grade, the tremie seal was placed and the rest of the South Pylon was constructed in the dry. Both lowering operations worked well and everything went smoothly.
**Conclusion**

The foundation design and construction team on the Sutong Bridge have succeeded in constructing foundations for a world record setting bridge at a very challenging site on the lower Yangtze River. The design team, working in conjunction with their construction counterparts, developed innovative holistic solutions that addressed the very rigorous requirements of the structural design while remaining fully constructible under extremely difficult conditions.

**Acknowledgement**

The authors wish to thank the Jiangsu Provincial Sutong Bridge Construction Commanding Department for the opportunity to assist them on this very challenging bridge project.

**References:**


**Appendix:**

1. Fig. A-1 MAIN SPAN SIDE ELEVATION
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Fig. A-3 MAIN PYLON CAISSON DETAILS
Fig. A-4 CAISSON LOWERING SYSTEM – STAGE I
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Fig. A-6  SCOUR PROTECTION DETAILS AT MAIN PYLONS
Fig. A-7  SCOUR PROTECTION PLAN