Design and construction of scour protection for deep-water group pile foundation structures of two pylons in the Sutong Bridge project

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Abstract: Sutong Bridge, as a world-record cable-stayed bridge with its main span exceeding 1 000 m constructed in Yangtze River estuary region in China, is located at a site with complicated hydrologic conditions and poor geotechnical conditions and therefore, scour protection will be a decisive factor for ensuring smooth and successful construction of this bridge. This paper, starting from structural description of deep-water group pile foundation, analyzes impact to the bridge safety introduced by scour and its protection and further presents different solutions of scour protection for foundation structures of this bridge.

Key words: Sutong Bridge deep-water group piles; scour protection; design; construction

1 Introduction

Riverbed scour protection is very critical for the success of building a bridge. China and some other countries have seen many collapsed or destroyed bridges due to scour. China Academy of Railway Sciences subordinated to the Railway Ministry, after a thorough investigation over more than 60 destroyed bridges of large or medium scale, has pointed out that most of these bridges were destroyed by flood scour or insufficient buried depth of foundation. After analysis of 143 severely damaged bridges throughout the world, Mr. D. W. Smith, Chief Engineer of British Bridges Association, found out that nearly half of these bridge accidents are due to flood scour. In 2000, some experts including E. V. Richardson, pointed out in *Scour Calculations for American Bridges* that huge amount of money were spent to maintain and repair damaged bridges in Unites States. There are at least 575 000 bridges in United States, among which 84 % are river-crossing bridges and 60 % of river-crossing bridges are damaged due to channel instability and riverbed scour. Riverbed scour has become a top challenge for bridge engineers all over the world. Sutong Bridge is located in Yangtze River estuary region and is featuring complicated hydrologic conditions, poor geotechnical conditions and severe scour. As a result, scour protection will be vital for the success of this prjecct. This paper presents a brief introduction to the design and construction of scour protection for deep-water group pile foundation structures of two pylons in Sutong Bridge and hopefully, this will provide reference for constructing similar projects in the future.

2 Hydrologic and geotechnical conditions

The river is alluvial and highly volatile with large morphological changes. Datong hydrologic station, approximately 480 km upstream of Sutong Bridge, is a station to control run-off in the main stream of the Yangtze River. Statistics from 1950 to 1997 show that average flow for many years is 28 255 m^3/s, the maximum flow (normally in July and August) is 92 600 m^3/s and the minimum flow (normally in January and February) is 4 620 m^3/s. Run-off is not evenly distributed over a year. Period from May to October is defined as flood season with average flow of 39 300 m^3/s. During flood season, water flow and discharge of suspended sediment are occupying 70.6 % and 87.5 % of annual run-off and discharge of suspended sediment respectively. Further the river . section where Sutong Bridge located is subjected to the astronomical tide and the fresh water run-off. During dry season, tidal current boundary of the Yangtze River can move upstream to nearby of Zhenjiang City, while during flood season, tidal current boundary can move downstream to nearby of Xijiegang Village. Hydrologic and morphologic survey results in the past decades show that ebb current is the main driving force to shape morphology of this channel. Flux and ebb current velocity for south pylon with 300 years return period is

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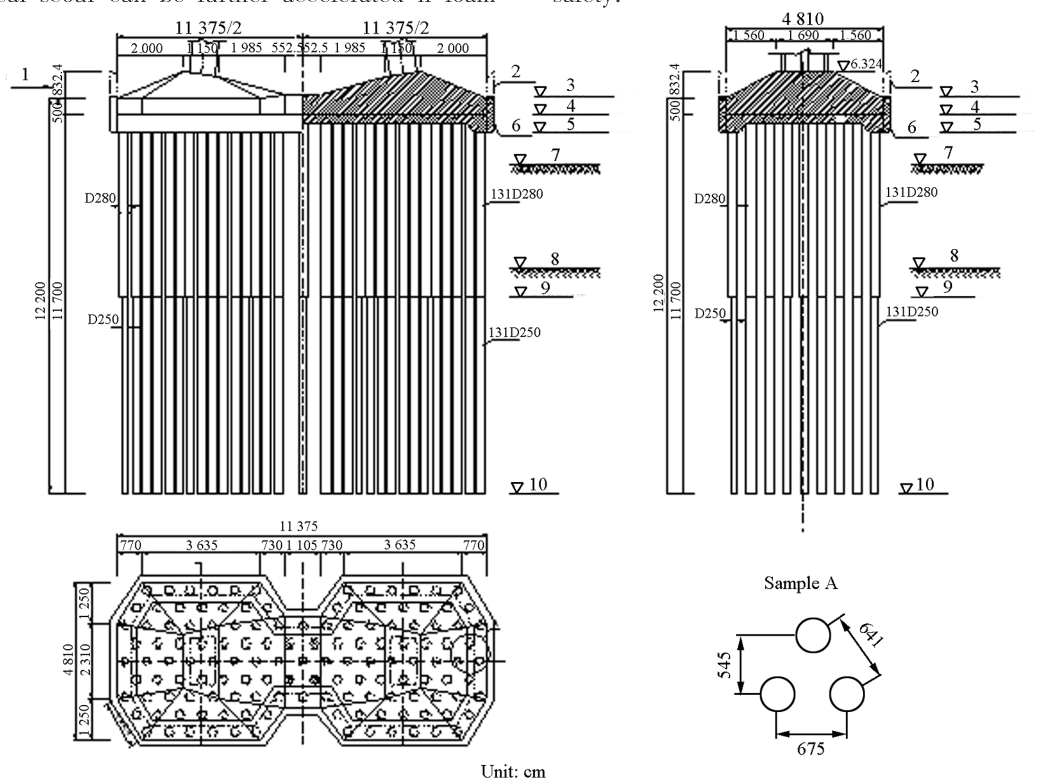
3.03 m/s and 3.40 m/s respectively. Flux and ebb current velocity for south pylon with 20 years return period is 2.73 m/s and 2.89 m/s respectively. Flux and ebb current velocity for north pylon with 300 years return period is 2.95 m/s and 3.28 m/s respectively. Flux and ebb current velocity for north pylon with 300 years return period is 2.62 m/s and 2.75 m/s respectively.

Sutong Bridge north pylon is in the northern side of deep channel with river bed elevation around −27 m. In this area, the riverbed mainly consists of sandy material and further are sandy loam, 28.5 m thick silty loam, 2.1 m thick loam clay and fine sand. South pylon is located on an edge slope in the southern side of deep channel with riverbed elevation around −15 m. In this area, the riverbed mainly consists of 6.5 m thick silty loam clay, 28.0 m thick loam clay and fine sand. Although silty loam clay has good resistance against scouring, the thickness of silty loam clay layer near south pylon is relatively small and sand in this area is very fine with average grain size of silty loam in a range of 0.12 ~ 0.16 mm. Moreover, the riverbed is highly volatile riverbed with small starting velocity and therefore, under high flow velocity at bridge site, the riverbed is featuring large local and widely-spreading scour. Local scour can be further accelerated if loam clay is subject to severe scour.

3 Structural description of deep-water group pile foundation[1]

The main pylon foundations are both supported by 131 bored piles with diameter 2.8 m/2.5 m (The external diameter of the steel casing is 2.85 m and the diameter of concrete bored piles is 2.5 m) respectively, which are shown in Fig. 1. The piles are designed as friction type piles with length of 117 m and are arranged with a spacing of 6.75 m. The steel casing is designed to participate in force transfer. The pile cap is shaped as a dumbbell. The dimension of the half symmetrical pile cap is 51.35 m × 48.1 m, the thickness is varied from 5 m at the edge to maximum 13.324 m. The two caps under the two pylon legs are connected by a cross beam with dimension of 11.05 m × 28.1 m and 6 m thick. It is found by local scour test that deep scour occurred to a depth of about 21.5 m for north pylon foundation for current with 20 years return period and a depth of 27.2 m for north pylon foundation for current with 300 years return period. Moreover, the maximum scour might occur during one time flooding, which will pose a great threat to foundation safety.



1—Direction of navigation;2—Remove part of the stell cofferdam; 3— -1.800 m (remove level of the stell cofferdam); 4— -7.000 m (bottom surface of the pile cap); 5— -12.500 m (bottom surface of the subsealing); 6—The concrete silo- wall;7— -26.423 m (ground line); 8— -52.190 m (The largest erosion line); 9—Bottom elevation of protective cylinder; 10— -124.000 m (bottom level of pile)

Fig. 1 General design of pylon foundations in Sutong Bridge

The key factor factor to foundation design is to ensure sufficient penetration depth of steel casing into the soil. Steel casing shall be driven to an elevation of −64.0 m provided riverbed scour is not taken into account. However, there is a layer of hard sand layer with thickness approximately 2.0 ~ 4.0 m at elevation of −52.0 m to −54.0 m and it is very difficult to drive steel casing here. As a result, scour protection must be implemented to avoid too excessive scour in riverbed. By doing so, it is acceptance to drive steel casing into the elevation of −52.0 m, which will avoid the occurrence of crimped steel casing due to vibrant driving.

There are two very critical construction activities during deep-water group pile foundation construction in Sutong Bridge, namely establishment of bored pile construction platform and lowering of extra-large steel cofferdam. Dense supporting piles and huge steel cofferdam will inevitably change water flow pattern and accelerate riverbed scouring, which will further reduce penetration depth of steel pipe piles and steel casings into the soil, decrease bearing capacity and jeopardize foundation safety. Local scour tests were carried out during construction to find out the impact on foundation construction safety imposed by scour. For south pylon, this test was performed on the prerequisite of taking current velocity at piers as 2.5 m/s (with 5 years return period) and water level as 3.0 m (water depth approximately 18 m). The test results showed that on completion of driving of all steel pipe piles, the maximum scour depth reached 17.4 m, the area with scour depth over 5 m covered 215 m × 180 m and penetration depth of steel casing into the soil is reduced to half of original value and after lowering of steel cofferdam, the maximum scour depth reached 21.5 m and the area with scour depth over 5 m covered 235 m × 180 m. In summary, riverbed scour is seriously jeopardizing foundation construction safety and therefore, it is absolutely necessary to carry out riverbed pre-protection during construction.

4 Scour protection concept for deep-water group pile pylon foundations

According to foundation design scheme, riverbed pre-protection must be implemented to ensure safety during foundation construction and accordingly, riverbed permanent protection must be implemented to avoid excessive scour and further ensure foundation safety during operation of the bridge. In Sutong Bridge, this new concept combining both riverbed pre-protection and riverbed permanent protection was adopted.

Scour protection concept mainly consists of two categories, i.e. energy dissipation to reduce scour and riverbed protection to resist scour. The former can effectively decrease current velocity and move forward scour pit to reduce scour depth within periphery of foundation. However, Sutong Bridge pylon foundation is located in a deep water and high current velocity environment and therefore, protection structure is subject to high impact from water current and large local scour. Considering stability of protection can not be assured and the concept of energy dissipation to reduce scour has never been tried in a practical project, the latter concept was adopted in Sutong Bridge[2-7].

According to the concept of riverbed protection to resist scour, riverbed can either be excavated or not excavated. In terms of these two alternatives, relevant tests were carried out to study the following three solutions, including riverbed protection structure parallel with riverbed (riverbed is excavated), riverbed protection structure lower than riverbed (riverbed is excavated) and riverbed protection by submerged island (riverbed is not excavated). Test results show that scour protection measures are functioning well to reduce or even avoid scour between piles and allow scour at pier side far away from bridge pier surroundings. Effect of scour protection with riverbed excavated or not is not obviously differentiating from each other, but riverbed protection results by establishing similar structures like submerged island but not excavating riverbed will be more preferable than those results achieved by solution of excavating riverbed. Test results also show that collapse settlement occurred at joint between riverbed protection structure and riverbed, which needs reasonable structural measures to adapt to this collapse settlement. Considering all above factors, a solution by establishing riverbed protection structure but riverbed not excavated was adopted in Sutong Bridge to protect riverbed and resist scouring. Additionally, lowering of falling apron structure is made to push the area susceptible to maximum scour depth far away from pylon foundation and adapt to collapse settlement of the riverbed.

The principle of falling apron is to utilize flexible contact between apron and riverbed and redistribution feature and dump some bulk material (such as stones) on top of protected slop or structure. When scour happens, bulk material will redistribute on scoured slope to retain original riverbed material so that further scour can be avoided. In order to verify the function of falling apron, comparison tests (with or without falling apron) were carried out. Test results show that in case of no falling apron, vortex around the foundation will be very obvious with relatively high scour depth and in case of available falling apron, the area susceptible to the maximum scour will be pushed far away and accordingly, the max scour depth will be decreased. According to test current velocity measurement, the maximum velocity area, after provided with falling apron, will be pushed to 30 ~ 70 m outside of falling apron and the maximum scour depth with 300 years return period will be decreased to 10 m approximately and the maximum scour depth with 20 years return period will be decreased to 8 m approximately.

5 Scour protection scheme of deep-water group pile pylon foundations

5.1 Distinctive division of scour protection areas

According to interaction mechanism between group pile foundation and soil and pattern of local scour, foundation can be divided into three distinctive areas: a. the inner area, which extends 20 m away from the pile cap, is the critical area for guaranteeing sufficient penetration depth into soil and bearing capacity and must be provided with sufficient protection as it is highly susceptible to the maximum local scour. b. the outer area, which extends further out from the inner area, is a critical area to guaranteeing proper foundation stress without major changes of stress mechanism and must be provided with permanent scour protection as it is subject to intense pile & soil interaction. c. the falling apron area, which extends further out from the outer area, shall be provided with apron structure to protect against riverbed scour as it has neglectable influence on stress state of group pile foundation.

5.2 Structural alternatives about scour protection works

Scour protection structures for Sutong Bridge must function well in the following three aspects, i. e. adapting to riverbed deformation, reverse filtering and erosion-proof effect. Meanwhile, protection structures shall be simple and lasting. Due to confined construction space on site, it should further be possible to construct the protection in smaller sections that together will constitute the protection. The final protection should be robust and able to function also with these unavoidable inaccuracies. According to requirements mentioned above, scour protection structure for Sutong Bridge is determined to consist of filter layer of quarry-run and armor stone layer.

Filter layer consists of sandbags, graded stones or soft mattress. Soft mattress is an efficient and economical filtering structure to protect riverbed. However, taking actual situation of Sutong Bridge pylon foundation construction into account, the solution of soft mattress is not adopted finally. Sandbag is also an efficient way to protect the riverbed and damage of small amount of sandbags during construction will not affect function of protection structure. Moreover, it has the advantage that it will allow for the construction of the piles through the central part of a temporary scour protection and then later on the final scour protection can be introduced. As a result, sandbags are chosen as a riverbed protection structure during pre-protection. Graded stone is an ideal filtering material and moreover, it is easy to construct and control forming rate. Therefore, graded stones are chosen as a filtering layer for permanent scour protection work.

Common armoring materials include armor stones, soil pillow, stone cage and interlocked concrete slab etc. Armor stone was finally chosen as it has many advantages, including convenient construction, cost-effective, adapting to riverbed deformation, small interference with pylon foundation construction and having effective compression over sandbags and graded stones in filtering layer.

In general, structural details of scour protection for Sutong Bridge pylon foundation are shown as follows (Fig. 2):

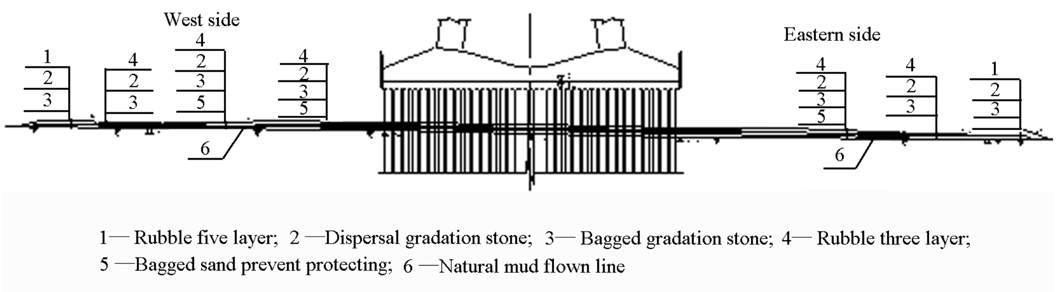


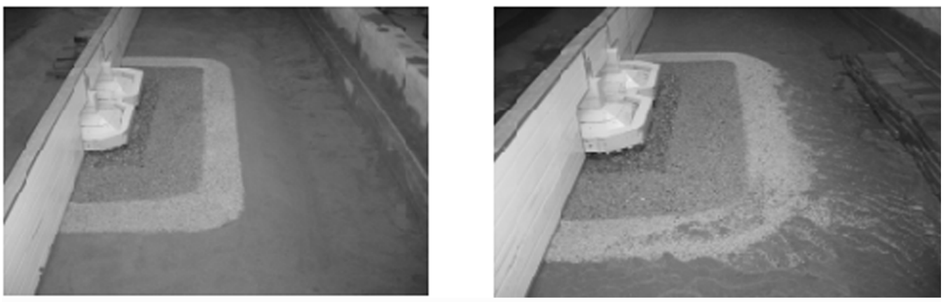
Fig. 2 Foundation protection structure

1) The inner area. In order to satisfy both pre-protection during construction and permanent protection during operation, the inner area consists of three layers, namely, sandbags directly dumped on riverbed for the purpose of pre-protection, on top of which is graded stones for the purpose of filtering and leveling and finally armor stones for the purpose of compaction and compression.

2) The outer area and falling apron area. Scour protection structure might consist of only two layers, i.e. graded stones and armor stones. However, dumping test of graded stones shows that dumped graded stones are buried very deep with low forming rate. As a result, sandbags were dumped prior to dumping of graded stones to facilitate forming of graded stone layer.

5.3 Structural design of scour protection work

On the basis of foundation dimension and extent of interaction between foundation and soil, the inner area of scour protection is determined to be within a range of 100 m × 210 m and permanent protection area extends 40 ~ 45 m further out of the inner area. In order to identify edge slope gradient of the falling apron area, scour stability test of edge slope was carried out with 300 years return period of hydrologic conditions (Fig. 3). Test results showed that except gentle slope of the falling apron area facing the water current direction due to side vortex action, edge slope of other parts in the falling apron area is in the range of 1∶2.1 ~ 1∶2.6. Width of the falling apron area for north pylon foundation will be calculated as 45 m provided that slope gradient is designed to be 1∶3.0 and width of the falling apron area shall be 1.5 times of the maximum expected scour depth. Similarly, width of the southern section of the falling apron area for south pylon foundation will be calculated as 30 m provided that the maximum expected scour depth in the southern section of the falling apron area is 20 m. Although the maximum expected scour depth in the northern section of the falling apron area is 30 m, width of the northern section of the falling apron area for south pylon foundation has to be 60 m. The reason is that additional 10 m scour due to channel sway has to be taken into account.



(a) Prior to the test (b) After the test

Fig. 3 Sketch of scour test of edge slope

Table 2 Planar layout of scour protection m

Main pylon	Dimension of construction platform	Dimension of the inner area	Width of the outer area upstream and downstream	Width of the outer area north and south side	Width of the falling apron upstream and downstream	Width of southern section of the falling apron	Width of northern section of the falling apron
North pylon	60 × 170	100 × 210	40	45	45	45	45
South pylon	60 × 170	100 × 210	40	45	30	30	60

The thickness of each protection layer in each protection zone is determined through tests. Structural scheme is as follows: a. Protection height of the inner area is 4.5 m, consisting of 2.0 m thick sandbag layer, 1.0 m thick graded stone layer and 1.5 m thick armor stone layer. b. Protection height of the outer area is 3.5 m, consisting of 1.0 m thick sandbag layer, 1.0 m thick graded stone layer and 1.5 m thick armor stone layer. c. Protection height of the falling apron area is 2.5 ~ 3.0 m, consisting of 1.0 m thick graded stone layer and 1.5 ~ 2.0 m thick armor stone layer. Test results show that this method can effectively protect the riverbed and resist the scouring. This method was further optimized on the basis of on-site tests during construction. Table 3 shows the thicknesses of each layer after optimization.

Table 3 Thickness of each layer m

Pier No.	The inner area			The outer area			The falling apron area			
	Sandbags	Graded stones	Armor stones	Sandbags	Graded stones	Armor stones	Sandbags	Graded stones	Armor stones in inner side	Armor stones in external side
North pylon	2.0	1.0	1.50	1.0	1.0	1.5	1.0	1.0	1.89	3.15/20
South pylon	1.5	1.0	1.50	1.0	1.0	1.5	1.0	1.0	1.89	3.15(3.78)/15(20)

Note: The number in bracket means the layer thickness for northern section of south pylon.

Stability test of scour protection materials with 300 years return period of hydrologic conditions was carried out to determine the size of sandbags and the weight of armor stones. Test results showed that compared with rectangular sandbags, square sandbags of the same weight in the same area are more stable. For the outer area and falling apron area, the size of sandbags is preferably 1.6 m × 1.6 m × 0.6 m and the weight of each sandbag is preferably 4.3 t. For the inner area, the size of sandbags is preferably 1.3 m × 1.3 m × 0.6 m and the weight of each sandbag is preferably 2.1 t. Armor stone has better stability performance and the weight of each armor stone is preferably 50 kg. The grain size of graded stones is preferably in a range of 3 ~ 25 cm and graded stones with the grain size of 3 ~ 10 cm and 10 ~ 25 cm occupy 50 % of total stones respectively.

6 Construction of scour protection work for deep-water group pile pylon foundations

6.1 Sandbags

Displacement of dumped sandbags and graded stones will be vital for the quality of scour protection. Therefore, prior to construction, trial dumping tests were carried out to find out the forming rate and drifting distance of sandbags and graded stones at various cross sections and under different water levels, current velocity and water flow direction. To perform the test, two 280 m^3 split barges were deployed in the inner area for south pylon to dump 1 000 m^3 sandbags and multi-beam echo sounder was used to survey at five different points. Test results showed that sandbags dumped by two 280 m^3 split barges, when landing to the bottom, spread into a regular elliptical shape and along the direction in perpendicular to the barge, spreading distance of sandbags is 4 to 5 times of openness width of the barge and along the direction in parallel with the barge, spreading distance of sandbags is almost zero. With current velocity smaller than 1.5 m/s, drifting distance is generally controlled within 10 m. When quantity of dumping materials reaches 100 ~ 200 m^3, better dumping effects can be achieved and dumped materials will spread and form a (20 ~ 25) m (length) × (8 ~ 10) m (width) regular elliptical shape. Based on the results of trial dumping, the following measures can be taken during actual construction. Divide scour protection area into a few sections on the basis of equipment capacity. The size of one section for north and south pylon is 15 m × 10 m and 25 m × 20 m respectively. Focus shall be made to construction in the inner area, dumping one layer first and followed by the next layer with survey results for the previous layer considered. For each section, two split barges were arranged to carry out simultaneous dumping, twice for each section with total dumping quantity of 400 m^3.

A positioning barge in parallel with water flow direction was used to dump sandbags and the barge is positioned via GPS supplemented with RTK (Real Time Kinematics) system. Manually fill sandbags directly placed in split barge with sand pump and make sure filling rate of sandbags shall be at least 75 %. Prior to dumping, calculate drifting distance according to real-time current velocity and direction and then move split barge to dump sandbags accurately. Single-beam echo sounder was used to monitor riverbed changes each day during dumping process and analyze dumping effect. Meanwhile, multi-beam echo sounder was used to monitor dumping effect every week. On completion of dumping operation by split barge, make additional dumping at favorable time with current velocity smaller than 1 m/s if underwater topographic map shows insufficient dumping at local area.

6.2 Graded stones

Trial dumping tests were also carried out prior to dumping of graded stones. During trial dumping, four split barges were deployed in protection area downstream of south pylon construction platform to dump graded stones. Trial dumping of graded stones is similar to that of sandbags. Test results showed that in case of current velocity not greater than 1 m/s, drifting distance is generally controlled within 10 m and in case of even smaller current velocity, dumped materials are rarely scattered. Construction procedure and methodology of graded stones for the outer area and falling apron area are basically identical with those of sandbags. The only difference is that a grab bucket crane located on positioning barge with a capacity of 200 m^3/h was used to load graded stones into the barge.

Most of construction area for graded stones in the inner area is just under main pylon construction platform and therefore, an opening with dimension of 2.6 m×3.7 m was designed to be made on the bottom plate of this platform. During platform construction, this opening was covered by a moveable hatch and during dumping of graded stones, this movable hatch will be removed. A crane with work radius of 17 m on the platform can be used to load graded stones into the barge and then an artificial dump truck can be used for dumping. For protection area around the platform, crane or jib crane can be used to lift and dump graded stones at specified position.

6.3 Armor stones

Both located dumping and random dumping were adopted to dump armor stones. Located dumping means choosing regular armor stones from stone yard, packing these stones in a steel wire net with diameter of ϕ 12 cm, transporting to construction site, hanging on positioning barge (with its own crane1.5 ~2.0 m^3), utilizing its crane to put in split barge and then dump at specified position. Random dumping means utilizing self-navigating deep-tank barge to transport armor stones to construction site, mooring beside the positioning barge, loading armor stones into self-navigating split barge by a crane and moving to a specified position and finally dump armor stones after GPS positioning. The latter method can facilitate dumping operation at area nearby main pylon construction platform.

Located dumping and rail solution were adopted for dumping of armor stones in the inner area. The former method is very similar to dumping of graded stones. The latter method means installing two sets of single-rail chain hoists on lower bracing of main pylon construction platform to dump armor stone. To be specific, each single-rail chain hoist was provided with two tuck nets with capacity of 1 m^3 and during installation, single-rail will extend 2 m further out from platform to facilitate loading of stones. Prior to dumping, trial dumping was carried out to find out drifting pattern of randomly-dumped armor stones in the inner area, which will be used as a basis and reference for formal dumping operation.

7 Monitoring of scour protection results

After completion of pile construction for north and south pylon foundation in Sutong Bridge, 1 : 1 000 multi-beam echo sounder was used to monitor underwater morphological changes at least 4 times. Survey rang covers 600 m further out to the south and north and 700 m further out to the east and west. Test results showed that scour protection effectively prevented erosion and achieved expected results. Fig. 4 and Fig. 5 show local scour around pylon foundation after completion of north and south pylon foundation pile construction.

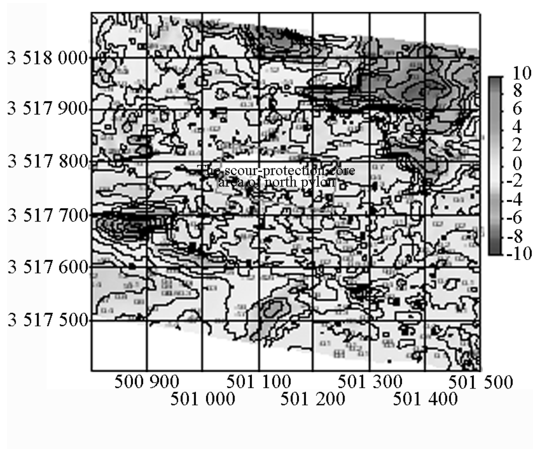


Fig. 4 Topography of north pylon with scour protection implemented

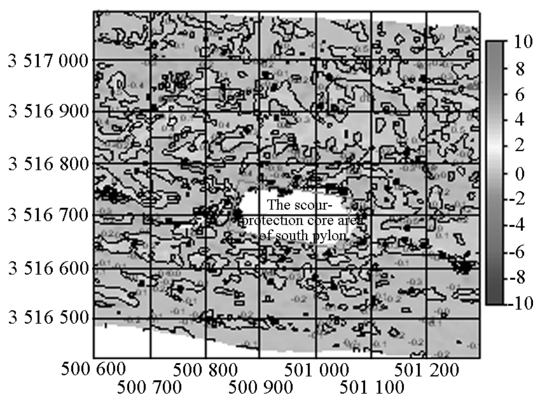
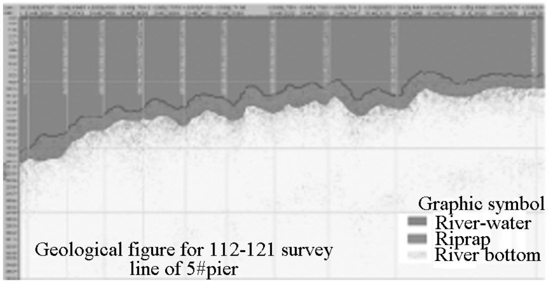


Fig. 5 Topography of south pylon with scour protection implemented

Figures show that the maximum local scour depth around north pylon foundation is approximately 8 m while the maximum local scour depth around south pylon foundation is only 1 ~2 m, which is much less than predicted value during test (10 m). Effective width of protection structure for north pylon foundation is only 190 m, smaller than total length of scour protection structure and is almost equivalent to the width of the outer area. This phenomenon indicates that on one hand, scour protection has effectively protected the outer area, and on the other hand, the falling apron area has experienced some local scouring during construction, which again confirms the necessity of scour protection. The existence of the falling apron restrained scour from further development toward pylon foundation and 1∶3 stable edge slop occurred at the area outside scour protection area with the maximum scour depth, which is in good accordance with model test results. This scour development pattern reaffirms the correctness of design concept of scour protection for main pylon foundation. Fig. 6 gives a profile of riverbed at a specified area on the basis of survey results by shallow stratum profiler, which again confirms the effect of scour protection.



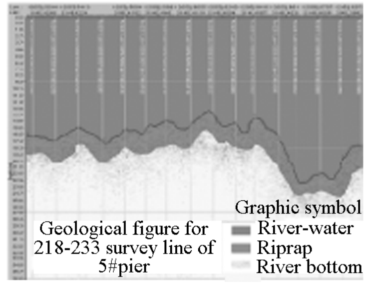


Fig. 6 Various cross section profiles of shallow stratum

8 Conclusions

Scour protection for Sutong Bridge pylon foundations is the first try to introduce scour protection to extra-large group pile foundation structures at erosion-susceptible riverbed in the estuary and based on this practice, the following conclusions can be made:

1) Permanent scour protection has been proved to be a feasible method to ensure structural safety for large-scale deep-water foundation susceptible to scour;

2) For deep-water foundation with complicated hydrologic conditions and confined construction space, scour protection for the purpose of protecting riverbed and reducing erosion can be implemented in distinctive layers and zones on the basis of structural stress mechanism and local scour pattern;

3) For deep-water foundations, a scour protection scheme combining pre-protection during construction and permanent protection during operation can help to ensure constructional and operational safety of the foundation and create better economic benefits.

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