Design of Scour Protection for Sutong Bridge, P.R. China

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This paper presents the results of scour assessment and conceptual design of scour protection structures for the Sutong Bridge, P.R. China. The SuTong Bridge, to date the Worlds Largest Cable-Stayed Bridge, is presently being constructed in the Yangtze River near the city of Nantong, P.R. China. The main pylons and approach piers are founded in the river and as a result they are susceptible to scouring of the erodible river bed. State-of-the-art methods have been used in the assessment and the design of scour protection for the SuTong Bridge. The designed scour protection primarily consists of quarry stones and is separated into three areas, Central Area, Outer Area and Falling Apron Area. During construction, extensive surveys using Multi-beam echo sounder were made in order to control and verify the amount of materials dumped. When finished, the scour protection is still a flexible structure that will be subject to some displacement of material. Therefore a detailed monitoring programme was prepared.

I. INTRODUCTION

The Sutong Bridge in the lower Yangtze River will be a cable stay bridge with approach bridges on both sides. It will thus cross the river with quite a number of bridge piers founded into the river bed. The main bridge will with its span of 1088 m be a world record cable stay bridge. The exact location of the Sutong Bridge is shown in Fig. 1.

The river is alluvial and highly volatile with large morphological changes. Further the river is subjected to the combined effect of the astronomical tide and the fresh water run-off and flow velocities can be very high exceeding 3.0 m/s in extreme conditions.

Therefore the river bed will respond almost immediately when introducing man-made structures such as bridge piers and pylons.

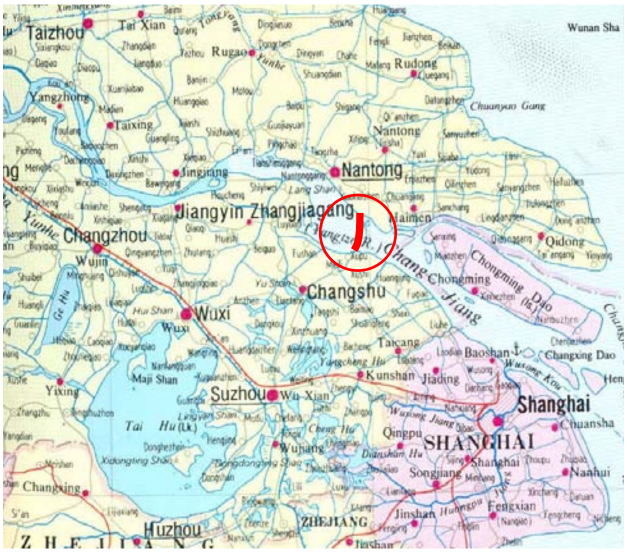


Figure 1. Location of Sutong Bridge, P.R. China

The present paper focuses on COWI's conceptual design of scour protection for the foundation structures of the two main pylons. Part of this work has been presented in [1].

II. HYDRAULIC DESIGN DATA

Design parameters are a combination of the current, water level and in some cases waves acting at the same time. To be conservative a 1/100 year return period wave has been combined with a 1/100 year current and the Mean Low Water Spring (MLWS). Details are outlined below.

Worst case for the scour protection is at low water level. The MLWS has been applied in the analysis:

MLWS: 1.0 m

The water depths at the two pylon locations are shown in Table 1.

The significant wave height for North and South Pylons are found in Table 1 where H_{max} can be taken as 1.8 x H_s. Corresponding wave periods have been assessed and also given in Table 1.

The design currents being a combination of tidal current and fresh water discharge are found in Table 1.

TABLE I.
SUMMARY OF HYDRAULIC CONDITIONS

Location	**Water depth, h [m]**	**Significant Wave Height, H_s [m]**	**Peak Period, T_p [s]**	**Current Velocity, U [m/s]**
North Pylon	30 m	2.24	9.0	3.06
South Pylon	16 m	2.52	9.2	3.18

III. RIVER MORPHOLOGY

A. River bed and geotechnical conditions at the site(s)

At the southern pylon, in about 20 m water depth the bed mainly consists of sandy materials. At the northern pylon, in about 30 m water depth the bed material is mainly silty loam and silty clay.

The natural material have approximately d_{50} = 0.1 mm in the main channel and lower elsewhere.

B. Future morphology development without the bridge

Without the bridge in place, the river may erode the river bed and change the position of the thalweg and river bank erosion may occur.

It appears from the bathymetric map, see Fig. 2, that there is a hardpoint immediately upstream of the bridge on the right bank. In Fig. 2 also two areas with potential for bank erosion have been marked.

Channel meanders have a bend radius of the order of 20 km. The main channel crosses from one bank to the other between bends. It seems the seawards flow is dominant in forming the river morphology. If an upstream bend is eroding, this may cause a shift in the channel pattern downstream.

The channel location at the bridge alignment seems controlled by the hardpoint immediately upstream on the right bank.

The river is the main waterway to the entire Yangtze Basin and the traffic by barges & boats etc. is very heavy. The banks of the river are controlled by river training works. The authorities regularly monitor the waterway, water depths and morphological development of the river and its bank protection. This is important to secure that the main thalweg stays in place under the main bridge.

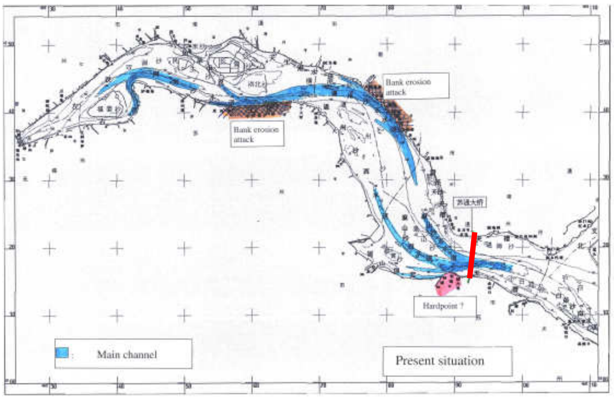


Figure 2. Present situation of the flow in the river

IV. BRIDGE PYLONS

A plan and cross-sectional view of the main bridge are shown in Fig. 3. The two main pylons consist of a pile cap located on top of a pile group. Horizontally the pile cap is approximately 48 m wide and 112 m long.

The following data applies for the piles:

Pile diameter:	2.5 m - 2.8 m
Distance between piles:	4 m - 5 m

V. DEVELOPMENT OF SCOUR PROTECTION CONCEPT

A. Scour assessment

As mentioned above, the Yangtze River is highly alluvial and carries a lot of sediment due to the high flow velocities. Therefore any man-made intervention obstructing the flow in any way will result in morphological changes, i.e. erosion or accretion of river bed material.

Table II and Table III are based on the results of the hydraulic model study made at Nanjing Hydraulic Research Institute for SuTong Bridge. They show results from the scour studies for different solutions including the solution now adopted using a foundation on large pile groups.

The scour depth is about 19 to 22 m and 17 to 19 m respectively for the S-pylon and N-pylon respectively. The differences reflect the difference in initial water depth of about 16 and 30 m at the pylons respectively, see Table II.

Besides the depth of scour for the no scour-protection situation an important aspect is the extent of the scour.

Table III shows the results of the studies.

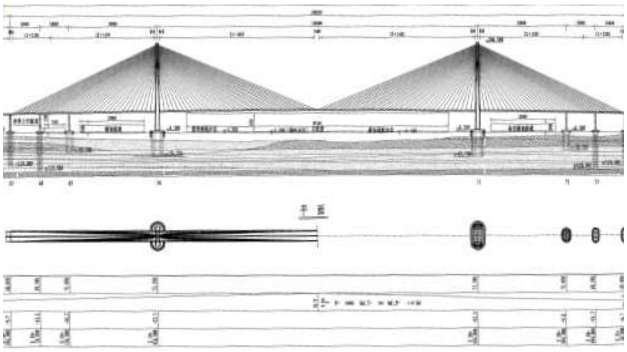


Figure 3. Plan and Cross-sectional view of main bridge

TABLE II.
MAXIMUM LOCAL SCOUR DEPTH

Position	**Foundation type**	**Return period (year)**			
		300	**100**	**20**	**5**
Main Bridge, South Pylon	**Cofferdam**	45.3	40.2	29.3	21.5
	Caisson (40 m x 88 m)	33.4	29.0	25.7	20.7
	Pile	21.9	19.1	16.2	13.5
Main Bridge, North Pylon	**Cofferdam**	41.2	35.5	27.4	20.4
	Caisson (40 m x 88 m)	30.4	27.1	22.7	18.7
	Pile	19.2	17.1	14.3	11.8

If again as an example, focus is made on the S-pylon and the solution for piles and 100 year Return Period, the extension of the scour from the centre of the pile group is 170 and 230 m in the N-S and E-W directions respectively. The extension is defined to where the scour depth is limited to 10 m.

Knowing that the pile group has a width of about 48 m and a length of about 112 m the extension of the scour from the structure is found as:

Extension, N-S Direction:	(170-48)/2 = 61 m
Extension, E-W direction:	(230-112)/2 = 59 m

It is interesting that the extension from the structure is about the same in all directions. This indicates that a scour protection structure should also in the first approximation have about the same width in all directions.

It is clear that it will be possible to design the bridge pylons to allow for such deep scour.

However, it was decided after geotechnical and structural calculations to include scour protection on the two main pylons, but not on all the other piers.

TABLE III.
MAXIMUM EXTEND OF SCOUR DEPTH OF 10 M

Position	**Foundation type**	**Return period (year)**	
		100	
		Width (m)	**Length (m)**
Main Bridge, South Pylon	**Cofferdam**	290	600
	Caisson (40 m x 88 m)	180	390
	Pile	170	230
Main Bridge, North Pylon	**Cofferdam**	260	580
	Caisson (40 m x 88 m)	170	350
	Pile	160	200

VI. CONCEPTUAL DESIGN

The ideas presented for scour protection have been developed based on COWI´s experience in combination with our understanding of the very difficult conditions in Yangtze River with deep water, high currents and high sediment transport as presented by the Client from other studies.

The major problem associated with the scour protection is its construction. The scour protection in itself shall be made in a way that it is not too difficult to construct and also that it will prevent scour during construction. It was assessed that if the bridge piers are made without prior scour protection the development of scour will be so rapid that it will 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 has been designed in such a way, 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.

It is further clear that due to the very high flow velocities and high sediment transport, the adopted scour protection scheme should be relatively simple and robust and not require very accurate dredging levels before placing of the material in the scour protection.

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.

COWI has on the basis of this analysis refrained from the use of large prefabricated mattresses, gabions or large bamboo/willow mattresses, etc. 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 include 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 shall be temporary protected by use of layers (3 nos.) of 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 is constructed with a filter layer of quarry-run and minimum 2 layers of armour stones (rock).

2. **Outer Area**
   Outside this the Outer Area is situated. It extends about 40 m further out from the Central Area, thereby the distance from to the edge to the structure is 60 m. This was based on a combined geotechnical and hydraulic assessment of the stability of the pile group. The scour protection consists of one layer of sand bags covered with a

layer of quarry-run on top of which is placed the same type of rock armor as for the central area.

3. **The Falling Apron Area**
   Outside the Central and Outer Area is the Falling Apron area. Its width is varying according to an estimate of the scour depth and the width is 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 are dumped.
   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/can be built. The principle is that the material in the falling apron will launch itself down the scoured slope that will thereby stabilize itself. It is previously been studied and used in [2].

The ideas developed have been turned into a conceptual design plan and cross-section for the S-pylon given in Fig. 4 and Fig. 5. This formed the basis for subsequent detailed design by Jiangsu Provincial Communication, Planning & Design Institute.

VII. SUPPORTING CALCULATIONS

A. *ASSUMPTIONS*

1) Amplification of flow

The presence of the structure under water will increase the flow velocity. This is taken into account through an amplification factor on the bed shear stress. The amplification depends upon the shape of the structure [3]. For a square-shaped structure the amplification of the bed shear stress is up to 3 for a 90 degree rotation and up to 9 for a 45 degrees rotation.

2) Critical Shields parameter

Incipient motion of stones resting on the river bed is characterized by a critical Shields parameter. A critical Shields parameter of the material used in the scour protection is shown in Table IV

Included in the critical Shields parameter value is a security that the stones is resting with no motion on the seabed for the inner and outer area. For sand bags in the temporary protection, it is not critical if there is a slight movement of the bags. For the falling apron it is emphasised that the materials are planned to mix and move down the slope.

B. *CALCULATION METHODS*

A short description of the method used for calculating the dimensions of the scour protection material is presented below. The Shields criterion is used to satisfy the stability of the top layer; namely, the Shields parameter calculated for scour protection material defined by

$$\theta = \frac{(U_{fm})^2}{(s-1)gd_{50}}$$

must be smaller than θ_{cr}, the critical value of the Shields parameter corresponding to the initiation of motion at the top layer of the protective layer. In the above equation, s is the relative density of the protection material, g is the acceleration due to gravity and d_{50} is the mean particle size.

TABLE IV.
CRITICAL SHIELDS PARAMETERS FOR SCOUR PROTECTION MATERIAL

Item	Location	Critical Shields parameter, θ_{cr} [-]
Stones	**Inner area**	0.025
Sand bags		0.040
Stones	**Outer area**	0.025
Sand bags		0.040
Stones	**Falling apron**	0.035
Stones at slope		0.025

U_{fm} is the friction velocity for the combined action of the steady current and waves. U_{fm} can be calculated from the following expression ([4] and [5]).

$$U_{fm} = \sqrt{U_{fw}^2 + U_{fc}^2 \left(1 + 1.2\left(\frac{U_{fw}^2}{U_{fc}^2 + U_{fw}^2}\right)^{3.2}\right)}$$

U_{fc} is the friction velocity based on the mean current velocity given by

$$U_{fc} = \frac{V}{\frac{1}{\kappa}\left(\ln\left(\frac{30h}{k}\right) - 1\right)}$$

Here κ is the von Karman constant equal to 0.4, h is the water depth and k is the grain roughness. The grain roughness, k, is taken as d_{50} for the stone material and for bed material it can be taken as $2.5d_{50}$. U_{fw} is the friction velocity based on the maximum orbital velocity at the bed, U_m, calculated by

$$U_{fw} = \sqrt{\frac{f}{2}}U_m$$

where f is the wave friction factor.

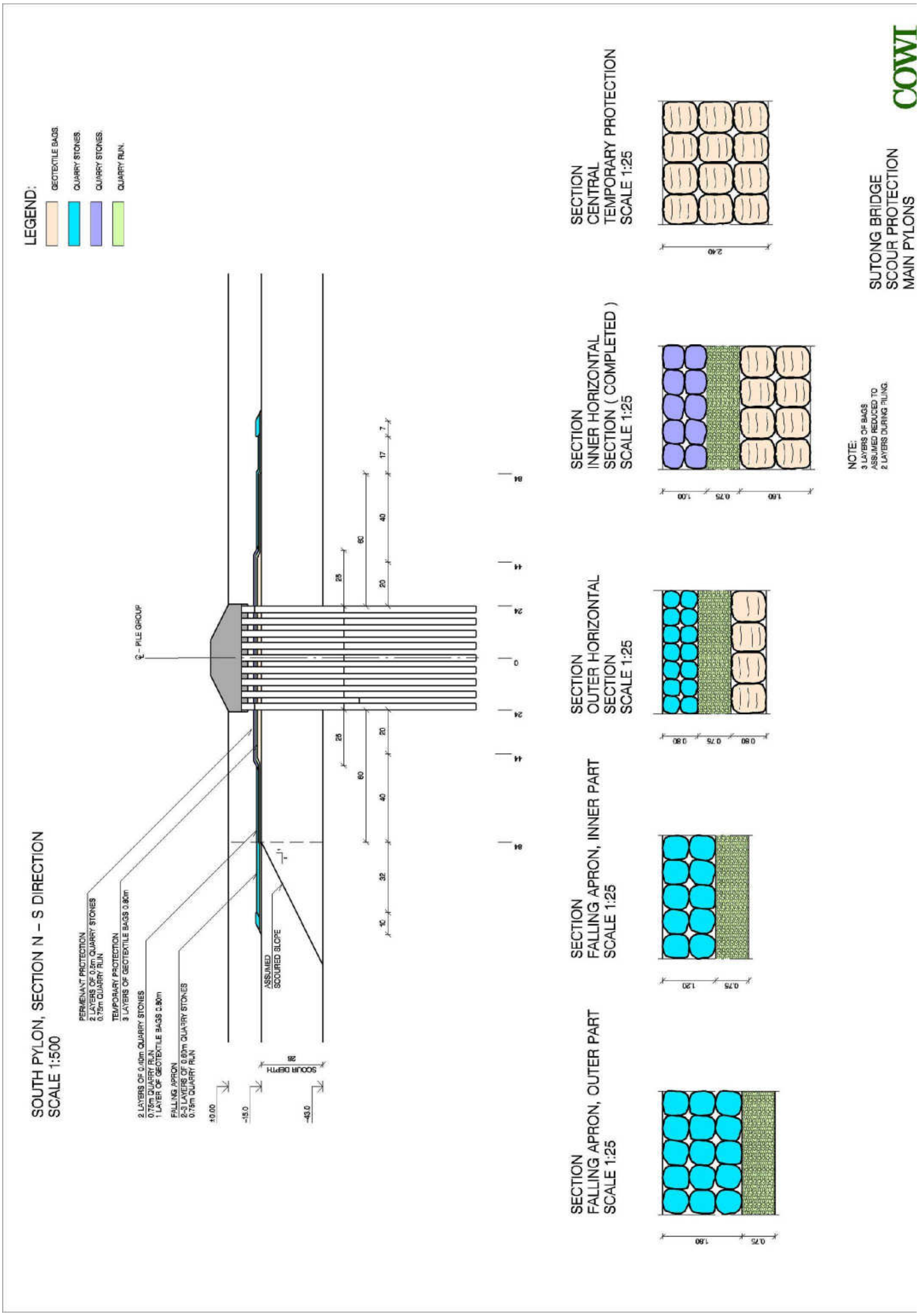


Figure 4. Scour protection layout - cross-section - South Pylon

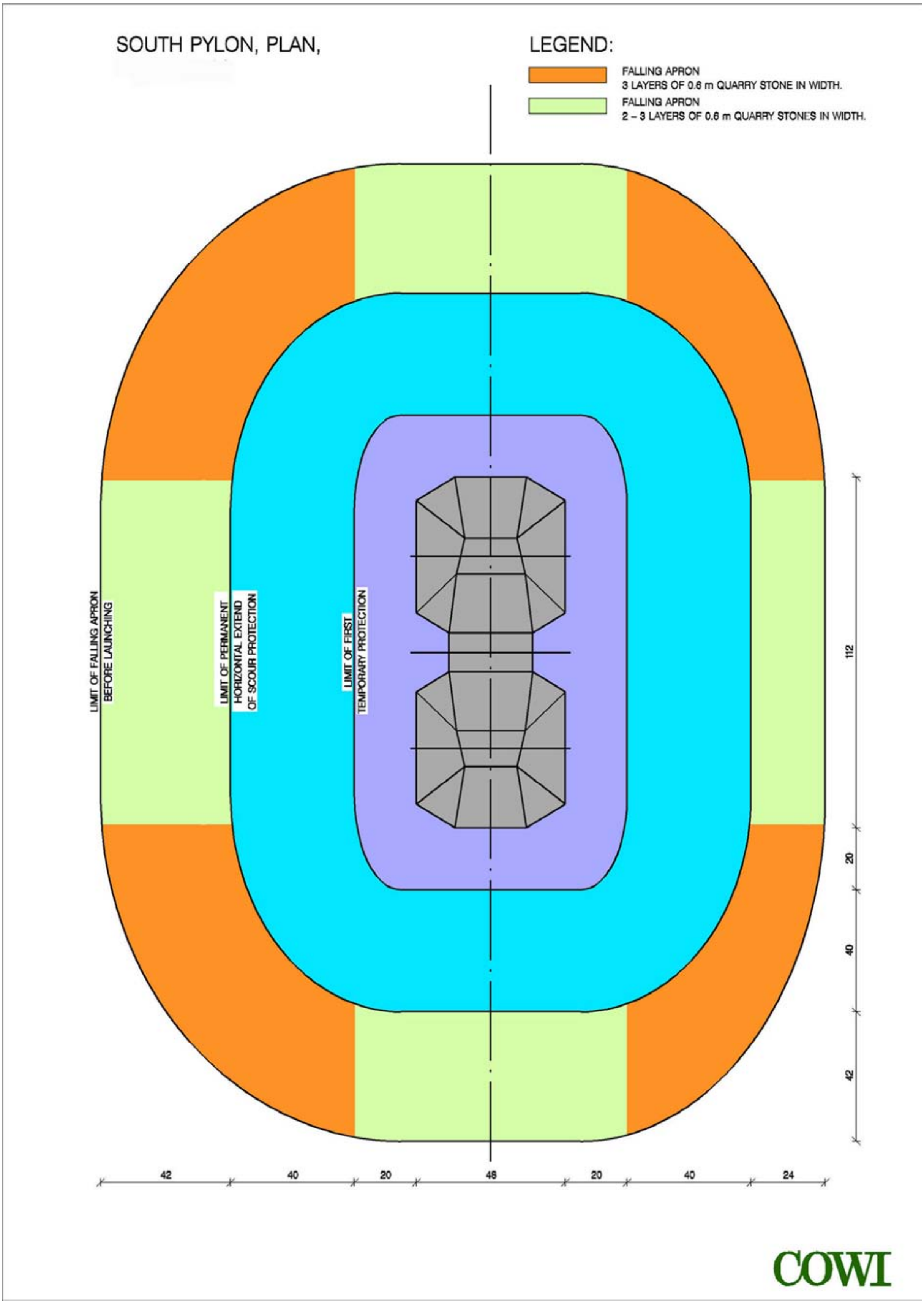


Figure 5. Scour protection layout - plan view - South Pylon

In case of sloping river bed the critical Shields parameter will be reduced by the following equation.

$$\theta_{cr,slope} = \theta_{cr} \cdot \cos(\beta)\sqrt{1-\frac{\tan(\beta)}{\tan(\phi_s)}}$$

Here β is the river bed slope and ϕ_s is the material friction angle. The river bed slope has been taken to 26 degrees (1:2) and the material friction angle has been estimated to 30-35 degrees.

For verification of the stone size the Izbash Equation has been used and the stones were found to be in the same order of magnitude.

C. RESULTS

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

It is found that the stone material is largest for the south pylon.

Further, the practical design should adopt the same size of bags all over and the same stone size for the outer area and falling apron. The actual sand bags used were of size: 1.6 x 1.6 x 0.6 m^3.

1) General Scour Protection Material

Grading of the material for the general scour protection shall comply with:

$$W_{15} = \frac{W_{50}}{1.5}$$
$$W_{85} = W_{50} \cdot 1.5$$
$$\overline{W} \approx W_{50}$$

Here W is the weight of the stone material for the fractiles 15%, 50% and 85%, respectively.

Below the stones a layer of filter material (quarry-run) characterised by d_{50} = 0.15 m (between 0.05 m and 0.25 m) shall be placed with a layer thickness of 0.75 m.

TABLE V.
STONE AND SAND BAG SIZE FOR THE SCOUR PROTECTION MATERIAL AT THE NORTH AND SOUTH PYLON

Item	**Location**	**Density [t/m^3]**	**d_{50} [m]**	
			North pylon	**South pylon**
Stones	**Inner area**	2.65	0.40	0.50
Sand bags		2.00	0.50	0.60
Stones	**Outer area**	2.65	0.30	0.40
Sand bags		2.00	0.30	0.40
Stones	**Falling apron**	2.65	0.30	0.40
Stones at slope		2.65	0.40	0.60

2) Falling Apron Material

The falling apron stones shall be graded as given above. References [6], [7] & [8] recommend the following on the design of the falling apron:

- Maximum predicted depth of scour, Y_s (m)
- Thickness of rock on slope face, T (m)
- Assumed scoured slope: 1V:2H (1:2)
- Length of apron on slope: 2.24Y_s (m)
- Assumed deployed apron thickness: 1.5 T (m)
- Volume of material: 3.35TY_s (m^3/m)
- Width of apron: WA = 1.5Y_s (m)
- Average thickness of apron: 2.24T (m)

Various authors suggest that the thickness of the apron be made larger towards its outer edge. COWI suggests that the above average 2.24 layers be distributed as follows. This is to make construction easier. Due to the critical conical shape of the corners more apron material is needed here. On these areas, see Fig. 6, three layers of stones should be used in the full width of the apron.

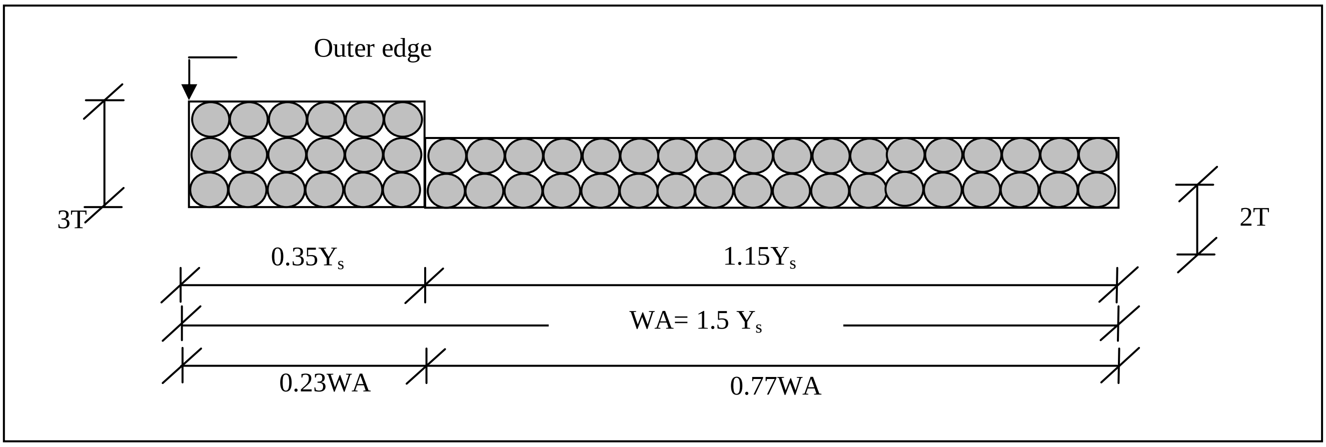


Figure 6. Falling apron details

VIII. EXPERIENCE FROM CONSTRUCTION

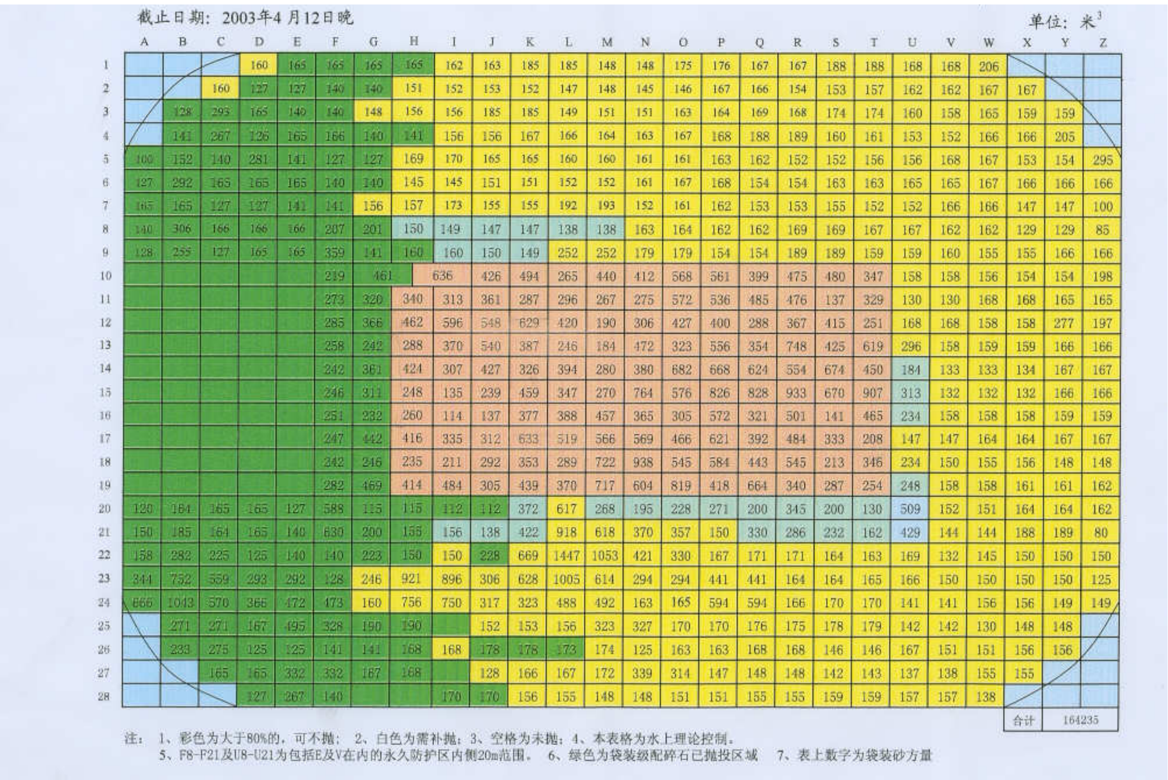
Extensive surveys using multi-beam echo sounder were made in order to control and verify the amount of materials dumped. The dumping of material was performed by split-barges using a grid with 28 x 26 cells (see Fig. 7) for the North Pylon and 16 x 16 cells for the South Pylon. Fig. 7 shows an example of the registration of volumes [m^3] in the protection of dumped sand bags within each control area. In connection with the distribution of the scour protection material acceptance criteria were established depending on two things, namely: (1) the type of material (sand bags, quarry-run or armour stones) and (2) the location of dumping.

Since the sand bags are a temporary protection, no criteria should be applied for acceptance. The experience from dumping of sand bags directly on to the river bed showed quite some penetration. Only half the volume of the sand bags was detected by the survey. Further due to the high currents and turbulence, the sand bags were displaced somewhat downstream from the barge and spread over a significantly area of the split barge itself.

The next layer of the structure, the graded stones has a design thickness of 1.0 m, meaning that the volume of material to be dumped should as a minimum correspond to 1.0 m of material. In reality the forming rate (recovery percentage) is less than 1.0 due to penetration of the graded stones in between the sand bags. It is therefore not required that 1.0 m thickness is present in the survey measurements. An absolute minimum for such filters is normally corresponding to 2 times d_{50} or 0.30m assuming that d_{50} = 0.15m as specified in the design. It was on this basis decided that the minimum requirements in the measurements should be 0.4 m for all the Areas: Central, Outer and Inner section of the Falling Apron Area. For the Outer section of the Falling Apron no Criteria should be applied, because here the apron might be eroding during construction due to scour at the edge and this is a natural process for which the apron is designed. The control for this outer section of the Falling Apron Area is thus that strict control is exercised on the volume of material to be dumped as well as the distribution of the material.

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

The above thicknesses have been determined as the difference between the in-survey (before dumping) and the out-survey (after dumping).



截止日期：2003年4 月12日晚

单位：米^3

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
1				160	165	165	165	165	162	163	185	185	148	148	175	176	167	167	188	188	168	168	206			
2			160	127	127	140	140	151	152	153	152	147	148	145	146	167	166	154	153	157	162	162	167	167		
3		128	293	165	140	140	148	156	156	185	185	149	151	151	163	164	169	168	174	174	160	158	165	159	159	
4		141	267	126	165	166	140	141	156	156	167	166	164	163	167	168	188	189	160	161	153	152	166	166	205	
5	100	152	140	281	141	127	127	169	170	165	165	160	160	161	161	163	162	152	152	156	156	168	167	153	154	295
6	127	292	165	165	165	140	140	145	145	151	151	152	152	161	167	168	154	154	163	163	165	165	167	166	166	166
7	165	165	127	127	141	141	156	157	173	155	155	192	193	152	161	162	153	153	155	152	152	166	166	147	147	100
8	140	306	166	166	166	207	201	150	149	147	147	138	138	163	164	162	162	169	169	167	167	162	162	129	129	85
9	128	255	127	165	165	359	141	160	160	150	149	252	252	179	179	154	154	189	189	159	159	160	155	155	166	166
10						219	461	636		426	494	265	440	412	568	561	399	475	480	347	158	158	156	154	154	198
11						273	320	340	313	361	287	296	267	275	572	536	485	476	137	329	130	130	168	168	165	165
12						285	366	462	596	548	629	420	190	306	427	400	288	367	415	251	168	168	158	158	277	197
13						258	242	288	370	540	387	246	184	472	323	556	354	748	425	619	296	158	159	159	166	166
14						242	361	424	307	427	326	394	280	380	682	668	624	554	674	450	184	133	133	134	167	167
15						246	311	248	135	239	459	347	270	764	576	826	828	933	670	907	313	132	132	132	166	166
16						251	232	260	114	137	377	388	457	365	305	572	321	501	141	465	234	158	158	158	159	159
17						247	442	416	335	312	633	519	566	569	466	621	392	484	333	208	147	147	164	164	167	167
18						242	246	235	211	292	353	289	722	938	545	584	443	545	213	346	234	150	155	156	148	148
19						282	469	414	484	305	439	370	717	604	819	418	664	340	287	254	248	158	158	161	161	162
20	120	164	165	165	127	588	115	115	112	112	372	617	268	195	228	271	200	345	200	130	509	152	151	164	164	162
21	150	185	164	165	140	630	200	155	156	138	422	918	618	370	357	150	330	286	232	162	429	144	144	188	189	80
22	158	282	225	125	140	140	223	150	150	228	669	1447	1053	421	330	167	171	171	164	163	169	132	145	150	150	150
23	344	752	559	293	292	128	246	921	896	306	628	1005	614	294	294	441	441	164	164	165	166	150	150	150	150	125
24	666	1043	570	366	472	473	160	756	750	317	323	488	492	163	165	594	594	166	170	170	141	141	156	156	149	149
25		271	271	167	495	328	190	190		152	153	156	323	327	170	170	176	175	178	179	142	142	130	148	148	
26		233	275	125	125	141	141	168	168	178	178	173	174	125	163	163	168	168	146	146	167	151	151	156	156	
27			165	165	332	332	167	168		128	166	167	172	339	314	147	148	148	142	143	137	138	155	155		
28				127	267	140			170	170	156	155	148	148	151	151	155	155	159	159	157	157	138			

合计 164235

注： 1、彩色为大于80%的，可不抛； 2、白色为需补抛；3、空格为未抛；4、本表格为水上理论控制。
5、F8-F21及U8-U21为包括E及V在内的永久防护区内侧20m范围。 6、绿色为袋装级配碎石已抛投区域 7、表上数字为袋装砂方量

Figure 7. Volume of sand bags dumped at each control area

IX. RECOMMEDED MONITORING PROGRAM

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 occur at its edges. Therefore a detailed monitoring program has been prepared. The program covers the entire bridge from the N to the S river bank.

In Fig. 8, the two survey areas are shown. Area A corresponds to a survey of the entire riverbed along the bridge alignment. Area B corresponds to a detailed survey of the scour protection around the main pylons. The recommended interval between each of the survey areas are presented in Table IV below.

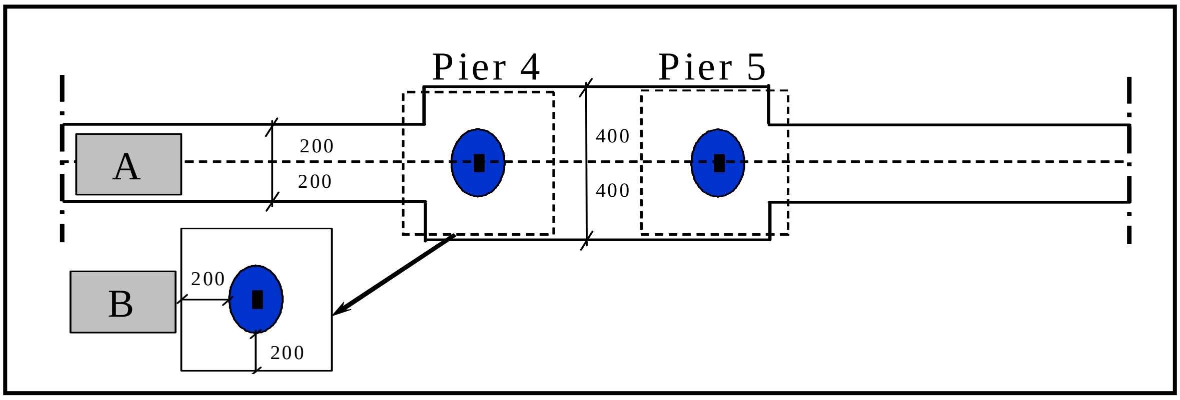


Figure 8. Survey area for monitoring program

TABLE VI.
RECOMMENDED MONITORING PROGRAM

Year	Month	Area A	Area B
2004	5	X	
	6		X
	7		X
	8		X
	9		X
	10	X	X
	11		
	12		
2005	1		X
	2		
	3		
	4	X	X
	5		
	6		X
	7		
	8		X
	9	X	
	10		X
	11		
	12		
2006	1		X
	2		
	3		
	4	X	
	5		X
	6		
	7		X
	8		
	9		
	10	X	X
	11		
	12		
2007	1		X
	2		
	3		
	4		
	5		X
	6		
	7		X
	8		
	9		
	10	X	X
	11		
	12		
2008	1		X
	2		
	3		
	4		
	5		X
	6		
	7		
	8		
	9		X
	10	X	
	11		
	12		

X. CONCLUSION

The paper presents the scour protection design for the Sutong Bridge in the Yangtze River. 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.

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