Design and construction of Sutong Bridge tower

Luo Chengbin[1], Zhou Jianlin[2], Tian Wei[3], Dai Jie[4]

(1. CCCC-Second Harbour Engineering Bureau, CCCG, Wuhan 430014, China; 2. Jiangsu Provincial Sutong Bridge Construction Commanding Department, Nanjing 210006, China; 3. Key Lab of Bridge &Tunnel Technology of CCCG&WHEDRI, Wuhan 430071, China; 4. Communications Planning and Design Institute of Jiangsu Province, Nanjing 210005, China)

Abstract: Sutong Bridge tower which is 300.4 m is the highest one in the world. The tower anchor area uses the steel-concrete composite structure, its structure and the stress mechanism are complex, so it must be paid more attention to the structure durable issue. The 300 m height makes the tower quite sensitive to the environmental factors such as wind and temperature. The wind resistance safety of tower in construction stage is especially important. In this paper, the design of composite structure is introduced. The key technologies of tower geometry control and wind resistance in construction stage are analyzed.

Key words: Sutong Bridge; tower; design; construction; key technology

1 Introduction

Sutong Bridge is the world's longest span cable-stayed bridge that has been built. The cable tower of the bridge is made up of reinforced concrete structure, and the height above the cable tower pile cap is 300.4 m. The anchorage of the cable-stayed bridge is an important part which is related to the structural safety. This bridge adopts steel anchor box anchorage system. In the design of the Sutong Bridge tower, it focuses on the studies of the tower anchorage area.

Sutong Bridge tower is located in the deep water area which is far from the riverbank, as a result of solar radiation, temperature changes, strong river wind and other natural factors, the impact on the realization of the liner control accuracy of the tower will be significant, and the construction process of the tower is influenced by the wind, the wind-induced response of the cable tower and tower crane is a key security concern of the tower construction.

2 General scheme

The whole height of the cable tower is 300.4 m, of which the height of the upper tower column is 91.4 m, the middle tower column is 155.8 m and the lower pylon column is 53.2 m. The space between the tower limb center and the tower bottom surface is 62.0 m. The section of the tower column is variable cross-section hollow box section, and it is solid paragraph at the bottom of the tower column. In the height of 64.3 m of the cable tower, the beam which adopting box variable-height structure is set up. The anchorage area of the cable tower uses reinforced concrete structure, of which the total number of the steel anchor box is 30 whose whole height is 73.6 m, and which is divided into A, B, C three types from top to bottom, among them, steel anchor box of class A and C has 1 block and class B has 28 blocks, the height of the standard segment is 2.3 ~ 2.9 m and the bottom section of the steel anchor box is 3.6 m. The bearing plate at the end of the steel anchor plate is linked to the concrete tower wall, the surface of which welding a shear wall which embedded in the concrete tower wall; the steel anchor box of the end section is linked to the concrete tower column which is used to transfer vertical component of forces of the cable-stayed bridge[1]. The general design drawing of the cable tower is shown in Fig. 1.

The cable tower uses hydraulic climbing form construction (the solid segment at the bottom uses stent slip form construction). The construction is divided into 68 segments, and the standard segment is 4.5 m high. The beams of the cable tower uses support cast-in-place, which is asynchronous construction with the tower column. The steel anchor box uses the construction of factory production, pre-fight, on-site installation, bolted method. In the middle and lower tower, at a certain height set the level support to impose active top-pillared force in order to eliminate the deformation and stress caused by the tilt of the tower column[2].

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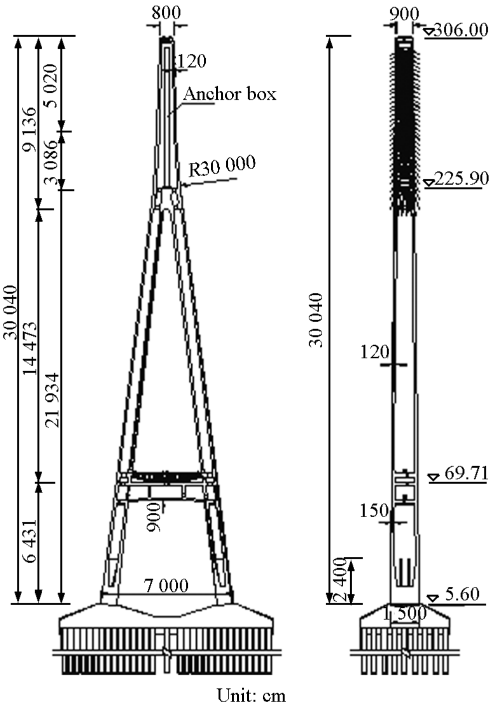


Fig. 1 The general design drawing of the cable tower

3 The design of the anchorage area of the cable tower

The anchorage of the cable-stayed bridge is an important part which is related to the structural safety, this bridge adopts steel anchor box anchorage system. The size of the structure is shown in Fig. 2. There are 30 blocks steel anchor boxes of Sutong Bridge, anchoring from 4^{th} to 34^{th} pairs of stay cable. Shear connector is a co-stressing key structure for concrete and steel anchor boxes, the diameter of the shear pin that this bridge used is ϕ 22 mm, the length is 200 mm and the ultimate strength is no less than 400 MPa (according to GB/T10433-2002). This welding nail is welded in the steel plate by special welding machine, whose construction is very convenient, having very small impact on the steel itself.

3.1 Simulation test of shear pin in anchoage zone of the cable tower

According to the forced state of the shear pin which is between the end-plate steel anchor boxes and the tower of the concrete, determining the stiffness and the bearing capacity of the shear pin through the experimental research, giving the shear rigidity and shear strength allowable value of the shear pin when used for numerical analysis. The photo of the shear nail sample is shown in Fig. 3.

The whole numerical analysis for the anchorage

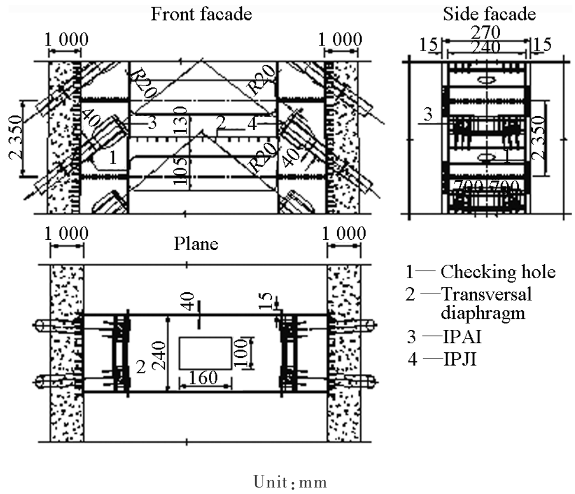


Fig. 2 The structure of the steel anchor box for cable tower

Fig. 3 Shear pin sample

zone of the cable tower has gotten the vertical shear stress for steel anchor boxes and concrete cable tower and the distribution of the shear for the shear pin, which results are closer to the structural analysis results of anchor zone. The test results of the shear nail show that:

1) The shear strength and shear stiffness of the shear pin will increase with the increasing of the pre-pressure; it was based on the safety that does not consider the friction between the end-plate steel anchor boxes and concrete tower wall during the design;

2) The shear strength of the shear nail adopts the secant stiffness cited in the 1/3 load service of the shear strength (Fig. 4), based on the performance test obtained the shear stiffness is about 220 kN/mm;

3) Supposing the load corresponding to the intersection point of the curve and the straight line which is caused at the place where the relative displacement of shear studs is 0.2 mm and the straight line should parallel to the secant line of stiffness. Taking the yield capacity considering the 1.7 times safety factor as the capacity allowable value, obtained by the shear nail performance

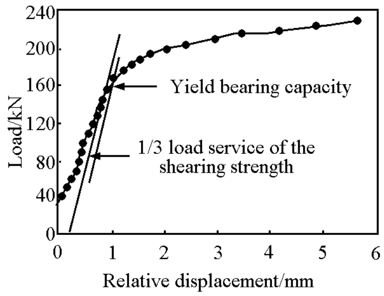


Fig. 4 The load-deformation curve of the shear pin

test, the capacity allowable value is 89.2 kN.

3.2 Model calculation of the anchorage zone tower

The calculation used space finite element to establish the cable model of the entire area, the concrete adopted solid element and the steel anchor boxes adopted shell unit. Using spring element to simulate the deformation properties of shear nail between concrete and steel anchor boxes. In the anchorage area of the steel anchor boxes cable, imposing the largest vertical component force to the cable under normal service conditions. The constraint form for the bottom of concrete tower column and steel anchor box was consolidated, in which process considering the contract and gradual change of the concrete. The vertical force of the stay cable was transferred to the concrete tower by three ways which contains shear pin, side friction and bottom supported, among which the side friction was considered as safety reserves, not included in the structural analysis. The key of the analysis of vertical force was how to accurately simulate the shear stiffness of the shear pins, the shear stiffness used for calculating was adopted by model test. The load-deformation curve of the shear pin gotten by shear test was shown in Fig. 4. The shear rigidity under the normal using load of the shear pin in a diameter of 22 mm was 220 MN/m. The calculating model and the results were shown in Fig. 5.

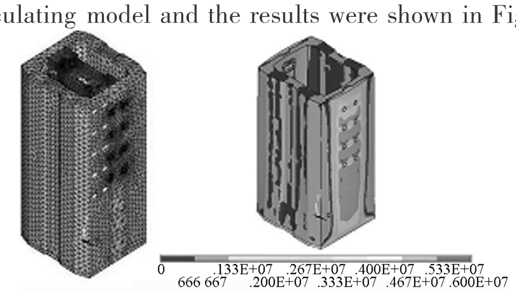


Fig. 5 Calculating finite element model and test results of the anchorage zone

3.2.1 Durability analysis of the structures

The test results show that the tensile stress of the concrete is bigger than the cracking stress of the concrete, the concrete cracks occur, once the tension area of the concrete cracking, the components will get into the work place with cracking and the stiffness have a significant reduction. It should do discount for the short-term stiffness which in the largest tensile stress department of the concrete, the stress of the concrete wall after discount is shown in Fig. 5. The nominal largest tensile stress of the concrete tower was 5.33 MPa.

According to the nominal tensile stress of the cable tower, it could calculate the distribution of the level of internal force of the cable tower and do structure reinforcement calculation under ultimate bearing capacity and normal service condition. The results of the calculation of steel show that, the design of anchor zone concrete is controlled by cracking, through reasonable reinforcement, the final calculation cracking width is controlled within 0.2 mm. The full-scale model tests show that the cracking width is about 0.14 mm under normal using load, and the cracking width is 0.17 mm under 1.7 times of normal using load.

In the anchorage zone of pylon of the Sutong Bridge, it set up dehumidification system which provides a permanent protection on the steel anchor boxes and stay cable anchor structure.

3.2.2 Rationality analysis of the structure

The results show that the shear pin design meets the bearing capacity requirements, but the horizontal shear pin bore uneven loading. The failure mode of the shear pin is the shear fracture in the root and no destruction in the welding parts; under the service ability limit state, the bottom concrete bearing the support reverse force is 600 MN, taking 20 % of the vertical load. The maximum compressive stress of the concrete is −25 MPa, without too much stress concentration occurs.

The on-site monitor show that in the early installation of the steel anchor boxes, the load of the steel anchor box is almost entirely born by the bottom concrete, and with the increasing of the construction segments, the load-sharing of the concrete tower wall increases. When the cable tower's construction reached to 270 m, the concrete tower wall would undertake 60 % of the total load. The stress level at the bottom of the steel anchor box is low, about −14 MPa, which is consistent with the design.

4 The liner control of the cable tower

4.1 The request and difficulty of the form controlling

The height of the Sutong Bridge is big and the middle and lower tower component is tilt, the controlling of space geometric position, alignment and precision is not only a routine but also an important task. In addition, the accumulation of the root tower moment and the additional stress caused by the self-loading of the tower column and the horizontal component of the construction load. Taping into tower, under the benchmark condition, the goal line pylon must meet the following error requirement: a. the slope error of the cable tower is not more than 1/3 000, and the axis deviation of the tower is no more than 30 mm; b. the elevation deviation of the top of the tower is not more than 10 mm; c. the axis deviation of the tower column in the pile cap is not more than 10 mm; d. the section size deviation of the tower column is not more than 20 mm.

The analysis of the parameter sensitivity shows that: a. Temperature and wind load had a great impact on the accuracy of the construction. When the temperature gradient along the bridge tower is 10 ℃, the dissymmetry of the top-side of the tower will up to 354.3 mm and tower-column-top will up to 159.0 mm; when the temperature gradient cross the bridge tower is 10 ℃, the dissymmetry of the tower column will up to 160 mm and the top-side of the tower will up to 55 mm; even if the night temperature gradient along the bridge was only 2 ℃, the displacement of the tower-column-top along the bridge would reach 33 mm, beyond the design requirement. b. When the wind speed along the bridge was 15 m/s (the elevation of the bridge), the dissymmetry of the top-side would up to 37 mm. Therefore, the tower line of the cable tower must be amended of the temperature and the wind. At the same time, in order to meet the construction schedule, it requested to do all-weather measurement location operation.

4.2 Concrete segmental control

The Sutong Bridge construction measurement used tracing prism method. The principle was that: the spatial relation between a point which was on the completed segments and the point which was on the awaiting for construction section segment was determined, and the relative space position was basically not affected by the wind, temperature and other environmental factors. In the environment of low night temperature gradient and wind speed, doing accurate measurement to the reference point, and doing amendments to the wind and temperature, every point being measured in the awaiting construction section segment all took this point as benchmark doing the all-weather construction survey. It was shown in Fig. 6.

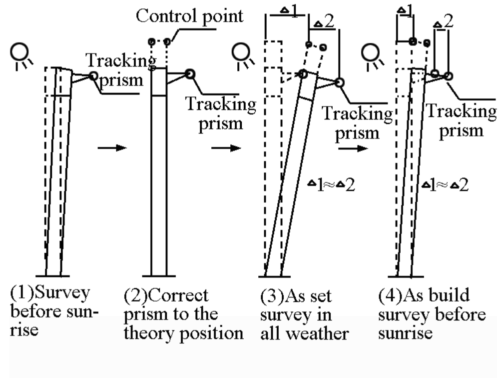


Fig. 6 The principle graph of the tracing prism method

This approach has the following advantages:

1) It can set out the work in the day time that must be carried out at night, lofting, measuring in the day does not need to do amendment of the temperature and wind, it can delay the treatment time for extending computing, data transmission such series work, and greatly improve the work efficiency;

2) Through the transmission of the relative position of the adjacent segments lows the elevation transmission error.

During the construction, according to the different parts of the tower used different measurement methods:

1) The middle and low of the tower column is concrete structure with a small height and great structural rigidity, the reverse deformation caused by temperature gradient is less than 1 mm, and simply installing a prism will be able to meet the requirements of precision controlling;

2) The upper tower column is steel-concrete structures with a great height, and the reverse deformation caused by temperature gradient is bigger which can get to 5 mm when the temperature gradient is bigger. As a result, installing 2 prisms in the direction of the temperature gradient which are use to monitor the deformation of the reverse.

4.3 The installation control of the steel anchor box and line adjustment

Tower construction on the first step was the installation of the steel anchor box, and than concrete pouring. The installation error control of the steel anchor box was the key to control the construction of the upper tower column. The steel concrete box used bolt connection, once connected to form a whole, and it was difficult to adjust to the tower line. As a result, it took two sides measures:

1) Strictly control the manufacturing accuracy of the steel anchor box. The perpendicularity error of each segment of the steel anchor box was controlled within 1/5 000, the whole inclination error was controlled within 1/4 000 and the manufacturing error was tested by pre-assembly measurement.

2) Strictly control the installed accuracy of the fires section of steel anchor box. The allowable error of the inclination for the first section of the steel anchor box was 1/3 000, the anchor boxes were mounted on 4 independent level confined plate, when installing the confined plate controls the relative height difference was not more than 0.42 mm.

Nevertheless, the installation error is inevitable. According to the terms, the installed inclination of the first section of steel anchor boxes was 1/3 000, corresponding to the tower offset of 27 mm; the overall tilt of the creating steel anchor boxes was 1/4 000, corresponding to the tower offset of 20 mm; the installation plane position error of the first section of the steel anchor boxes was 5 mm, corresponding to the tower offset of 5 mm, if these errors were in the same direction it would lead to the tower offset get to 52 mm after superposition, beyond the design requirements of 30 mm, it was shown in Fig. 7.

In addition, the steel anchor boxes are welding structures with small structural stiffness. It will cause some deformation in the process of transportation and lifting having an impact on the installation precision. It must do error adjustment and control during the installation.

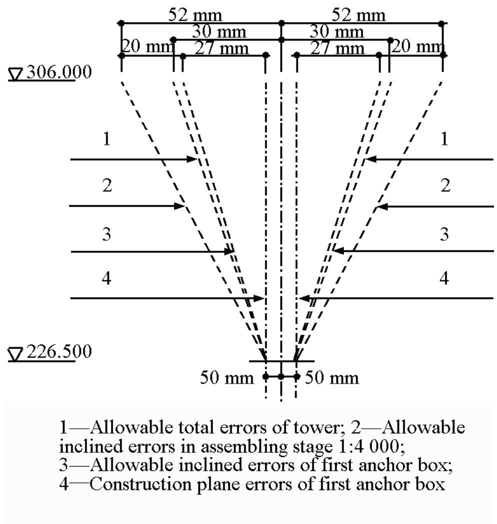


Fig. 7 The diagram of error control of cable tower construction

The error adjustment measures were: doing measurement and evaluation for the accuracy for the installed steel anchor boxes and evaluating the error trends for the follow-up segment, determining the timing of the adjustment; setting of 12 mm thick plate for every 4 anchor boxes segment, according to the need, doing fine machining to the gasket, adjusting the tilt error.

4.4 The results of the line control for the cable tower construction

The on-site measurements show that the axis deviation and section size error of the middle and lower segments was in the precision control, the errors of the on-site installation were controlled within the permissible error range (both the error of the elevation and axis are ±10 mm), the installation of the upper part of the cable-stayed structure provided a necessary anchor boxes. The error of the center section and section size was controlled in the error range (the tilt error of the tower column was not more than 1/3 000, and the axis deviation was not more than 30 mm; tower section size deviation was not allowed to beyond 20 mm).

5 Wind resistance and vibration control of the cable tower

The wind resistance safety of the 300 m high tower standing in the Yangtze River estuary is the issue that the bridge engineers must focus on. In the design stage, it conducted a pylon wind tunnel model test under a self-sustaining state in Tongji University, the test results show that the structure critical wind is much larger than the test wind; in the bridge-wind conditions, the tower will not have a divergent vibration and the structural strength and stability are guaranteed.

The pylon wind tunnel model test under a self-sustaining state of the construction phase was conducted in the Southwest Traffic University, its main purpose was to study the aerodynamic characteristics of the cable tower, tower crane and formwork system during the construction phrase, assess the safety of wind resistance during construction phase of the cable tower and the influences on the equipment and personnel operating conditions for the wind, and study the vibration reduction measures according to the results.

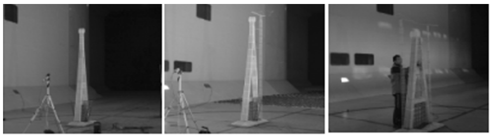
5.1 The wind tunnel test of the tower construction period

5.1.1 The test model

The ratio of the test model was 1∶100 (Fig. 7). The stiffness and quality of the cable tower was simulated according to similarity criteria, the crane only simulated the stiffness, the level support simulated the quality and the stiffness and other temporary structures only simulated the analog form. The experimental parameters were as follows: the test wind speed in uniform flow was 61.2 m/s, the respective damping ratio was 0.5 %, 0.8 % and 1.6 %; the test wind speed in turbulent flow was 45 m/s, the turbulence intensity was 5.5 %.

5.1.2 Test results

In the uniform flow and small turbulent flow tri-



Stage 1: tower as build | Stage 2: tower as build with equipment | Stage 3: before up-tower closure

Fig. 8 The wind tunnel test model of the cable tower

als, observed the vortex-induced vibration, the test results were shown in Table 1, the test show that: a. in the construction period, lower than the design wind speed of 35.4 m/s, it hasn't found the divergence amplitude phenomena; b. in the circumstance of design turbulence filed, it hasn't found significant buffeting response; c. in the condition of uniform and turbulent flow, vortex-excited resonance phenomenon along the bridge under the three conditions happens.

Table 1 The results of vortex-excited resonance test

Condition	Conditions	Uniform flow			Turbulent flow(5.5 %)		
	Damping /%	0.5	0.8	1.6	0.5	0.8	1.6
Condition 1	Most unfavorable angle/(°)	0	0	0	0	0	0
	Corresponding wind /(m·s^{-1})	12.8	13.0	13.6	13.2	12.8	12.4
	Amplitude /mm	457	82	21	225	48	16
Condition 2	Most unfavorable angle/(°)	3	3	3	3	3	3
	Corresponding wind /(m·s^{-1})	13.4	13.2	13.2	13.4	13.2	13.8
	Amplitude /mm	394	67	15	162	51	13
Condition 3	Most unfavorable angle/(°)	−1.5	−1.5	−1.5	−1.5	−1.5	−1.5
	Corresponding wind /(m·s^{-1})	27.1	27.4	27.4	25.4	25.4	25.4
	Amplitude /mm	52	23	14	23	15	4

5.2 The assessment and analysis of the wind tunnel test and the damping measures

5.2.1 The analysis of the test results

According to the results of the wind tunnel test, using proper value method to do aerodynamic response to the other seven construction segments from 154 m high to the whole high of the tower under construction phase to get the amplitude and acceleration value of the cable tower and crane which were shown in Table 2.

Table 2 The amplitude and acceleration value of the crane and cable tower for the construction phase

	The height of the tower /m	Wind speed /(m·s^{-1})	Amplitude /mm		Acceleration /(m·s^{-2})	
			Overhead	Tower ceiling	Overhead	Tower ceiling
1	306.0	12.4	137	178	0.106	0.138
		35.3	0	6	0.000	0.035
		12.9	187		0.157	
2	270.8	14.3	55	111	0.056	0.114
		17.5	1	1	0.002	0.002
3	248.4	17.3	11	45	0.013	0.052
		20.0	10	4	0.015	0.007
4	221.4	17.1	2	19	0.003	0.023
		21.2	19	129	0.037	0.249
5	212.4	21.5	5	51	0.010	0.101
		26.3	33	83	0.099	0.245
		25.4	45		0.125	
6	172.1	24.8	1	16	0.001	0.036
		41.0	47	32	0.292	0.199
7	154.0	42.9	7	71	0.046	0.438
		54.9	41	103	0.411	1.047

According to the results of the winds tunnel test, determining the focus of construction related to the working conditions, doing analysis and assess to the vibration of the cable tower and crane under construction and it concluded that:

1) Structural stress: the stress changes of the standard section and attached system caused by vortex-induced vibration (boundary wall bolt and link rod) were lower than the allows stress of the material;

2) Work comfort: the acceleration of the tower ceiling might be 13.8 cm/s^2, less than the work comfort limit acceleration of 30 cm/s^2;

3) The effect of the period: the entire height of the tower may arise vortex-induced vibration lower than the wind speed of 15 m/s, the probability that the construction period of the upper tower column occurred the wind speed of 11 ~ 15 m/s was 2.6 % ~ 5.8 %, therefore, the construction measurement could avoid this section of the wind speed, having little impact on the project.

5.2.2 Damping measures

From the experimental analysis results it can be seen that, there isn't great impact caused by the vibration to the tower construction and the crane interoperability. The vibration frequency is low, and it is not effective to suppress using active mass damper. So it needn't use damping measures to the cable tower and crane, but during the construction process, stopped the operation of top rise climbing model and the operation under crane loading state.

6 Conclusion

It described the world's first thousand-meter cable-stayed bridge—Sutong Bridge of the design calculation, the line control of the up-tower column as well as wind resistance under construction period of three key technology research, which provided a reference for the design and construction for the same type.

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Author

Luo Chengbin, male, was born in 1970. He graduated from HoHai University and now is a chief engineering in SNEB of CCCG, Wuhan, China. Mr. Luo has published over 10 papers. His current work is management of construction of long span bridge. He can be reached by E-mail: lcbwh@263.net

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novations, realize leaps in their development and make quicker improvement of core competitiveness of bridge technology in China. From "learning from others" to "self-initiated innovations", this is the only way to realize bridge technology innovations and create our own brands.

5 Conclusion

It is a strategic task to establish "a technical innovation system that regards enterprises as its main body, orients its development by market demands, and integrates industries, colleges and universities, and research institutes". Strategic tasks involve long-term interests, the common interests of the state, the society, and enterprises. Implementation of a strategic task means investments and efforts and means perseverance and patience. As the saying goings, "peach trees need three years to fruit, apricot trees four years, and pear trees five years, while date trees turn out money at the very year of planting." Now, figuratively, we're planting pear and apricot trees instead of date trees. Implementation of strategic tasks need joint efforts of the government, proprietors, and the society. At the present stage, it is even more necessary for proprietors to exert more efforts, bear the strategic interests of the state in mind, create good environment, vigorously cultivate enterprises, give them bigger platforms and spaces, and strengthen guidance and policy implementation and firmly promote the growth of their innovation capabilities.

Author

You Qingzhong, male, born in 1957, graduated from Southeast University in 1983, with a bachelor degree. Working as the director of Jiangsu Provincial Communications Department and the site director of Sutong Bridge Construction Commanding Department, he was involved in construction management of Hunning expressway, Jiangyin Bridge, Runyang Bridge and Sutong Bridge project. Issued more than 10 articles, he was currently involved in the study on Construction Management of Large Scale Transportation Infrastructure Construction. He can be reached by E-mail: YQZ@stbridge.com.cn

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