Technical and Economic Analysis of the Life Cycle of Huangmaohai Cross-sea Bridge

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Abstract: Huangmaohai Cross-sea Bridge has a total length of about 31 kilometers and adopts two-way six-lane design standards. There are 2 super large cable-stayed bridges, one of which is the Huangmaohai Bridge. It has a span of 720 meters, and after completion it will become the world's largest span three-tower cable-stayed bridge. Choosing the best plan in the project decision-making stage of large-scale cross-sea passage projects and other public construction products, eliminating blindness in plan selection, and optimizing the life cycle costs of the project can save a lot of manpower, material and financial resources for the country and society. According to the relevant concepts and classifications of the life-cycle cost of the project at home and abroad, this paper divides the life-cycle cost of China’s highwys into three types of costs: construction period cost, operation period cost and disposal cost, and carries out economic analysis in combination with main technical solutions. The analysis results strongly support the design scheme comparison and selection of the Huangmaohai Cross-sea Bridge.

1. Introduction

Huangmaohai Cross-sea Bridge Project starts from Gaolan Port District of Zhuhai, connects Hong Kong-Zhuhai-Macao Bridge in the east and Xin-Tai Highway in the west, intersects with the western coastal highway, and ends at Doushan Town, Taishan City. The total length of Huangmaohai Cross-sea Bridge is about 31 kilometers, of which the sea crossing is about 14 kilometers. It adopts the two-way six-lane design standard, with 2 super large cable-stayed bridges, 1 medium and 1 long tunnel, and 4 interchange points. The Huangmaohai Bridge, with a span of 720 meters, will be the world's largest three-tower cable-stayed bridge after its completion. As an important channel for the interconnection between the east and west sides of the Guangdong-Hong Kong-Macao Greater Bay Area, Huangmaohai Cross-sea Bridge, together with the Hong Kong-Zhuhai-Macao Bridge, Shenzhen-Zhongshan Link, Nansha Bridge and Humen Bridge, will form a cross-sea and cross-river corridor group of the Greater Bay Area and help the Greater Bay Area become a world-class transportation hub as soon as possible.

At present, a great deal of research has been done on the full life cycle cost analysis of bridges at home and abroad, and the corresponding calculation models and methods have been proposed. According to related concepts and classification of the project life-cycle cost at home and abroad, combined with the feasibility of highway construction cost management system and operation in China, costs of construction, management and maintenance, as well as the additional costs paid by the users and the society during the construction, operation and maintenance, should be considered in a complete full life period cost from the beginning of planning and design to the end of life and disposal, which
include costs of planning stage, feasibility study, design, construction, user, management, repair, maintenance and disposal. Among them, costs of planning stage, feasibility study, design and construction in the early construction stage are collectively referred to as the construction period cost, while costs of user, management, repair and maintenance are collectively referred to as the operation period cost, and costs of disposal are collectively referred to as the disposal cost. Therefore, the life cycle cost of highways in China can be divided into three categories: construction period cost, operation period cost and disposal cost. Each type of cost is subdivided into multiple related sub-types of costs.

Based on the life-cycle analysis concept and framework above, life-cycle cost analysis under different technical solutions are carried out in this paper for the Huangmaohai Cross-sea Bridge Project, so as to provide support for the selection of economic and reasonable technical solutions for the project.

![Fig. 1 Cost composition of the full life cycle of highway engineering](image)

2. Project overview and main technical scheme

2.1. Project overview

The project of Huangmaohai Cross-sea Bridge adopts the standard construction of six-lane highway with a design speed of 100km/h. Two navigable bridges are set on the whole line, namely Gaolangang Bridge (cable-stayed bridge with 700m main span) and Huangmaohai Bridge (three-tower cable-stayed bridge with 2×720m main span). The approach bridges in the sea have spans of 100m, 70m and 40m, with a total length of about 10.4km, while the approach bridges on the land have spans of 40m and 30m, with a total length of about 9.4km.

According to the bridge location scheme in the preliminary design stage of the Huangmaohai Cross-sea Bridge, the bridge engineering length accounts for about 70% of the line in the recommended scheme. Considering that the bridge engineering accounts for a large scale and is the control project, the comparison of the full life scheme of the bridge engineering of the cross should be analysed.

2.2. Main technical scheme of main bridge

Huangmaohai Bridge, the spans of which are set as 100+280+720+720+280+100=2200m, is a three-tower cable-stayed bridge with single-column towers and double-cable-plane. Its height to span ratio is 0.25 and side-to-middle span ratio is 0.53.
Figure 2 General Layout of Huangmaohai Bridge (Unit: mm)

(1) Main girder

Main girder schemes mainly include ordinary steel box girder, UHPC deck composite girder and steel-UHPC composite girder.

(2) Main tower

The bridge tower scheme is divided into single-column tower scheme and A-type tower scheme. Pile group foundation is adopted for the foundation of column tower. The diameter of pile is 2.8m, and the upper part of 30m is equipped with permanent steel protection cylinder, which is designed according to rock-socketed pile. The single column tower is divided into concrete bridge tower and steel-concrete bridge tower according to different materials.
(3) Transition and auxiliary piers

Pile group foundation is adopted for the foundation of transition pier and is designed according to rock-socketed pile. The T-type transition pier adopts round end shaped section and is 3.2m thick. The size in the transverse bridge direction gradually increases from the bottom of the cover beam (7m) to the bottom of the pier, and the bottom size of the pier is controlled by the height of the pier, with the unilateral change slope rate 1:25. The height of the pier roof beam is 6.3m, and the length in the transverse bridge direction is 40m. The auxiliary pier and transition pier schemes are the same.

(4) Cable

The stay cables are in the form of spatial double cable planes. There are 24 pairs of stay cables at each tower, and 3 pairs of auxiliary cables are set at the middle tower. The cable distance on the tower is 3m. The cable distance of the ordinary stayed cable is 15m along the girder, while the cable distance of the auxiliary cable beam is 30m, and the length of the no-cable zone is 15m. The stay cables are made of parallel steel cables with PE protection.

2.3. Screening of life-cycle technical solutions

According to the above technical schemes, the influences of each technical scheme on the construction period, operation period and disposal period are summarized, and the technical schemes that need to be compared and selected in the full life cycle are screened out.

| Table 1 Comparison and selection of the full life cycle of technical scheme of Huangmaohai main bridge |
|------------------------------------------------------------------------------------------------|
| Research scope | The overall plan | Local technical scheme | Construction period cost-type | Operation period cost-types | Disposal cost-type | Project cost Than choose stage |
| Main Bridges | Single column tower scheme | Main girder | Ordinary steel box girder | Single column tower girder A scheme | Single column tower girder A scheme | Single column tower girder A scheme | Full life cycle |
| | | | UHPC deck composite girder | Single column tower girder B scheme | Single column tower girder B scheme | | Full life cycle |
According to the analysis of the characteristics of the full life cycle cost of Huangmaohai Bridge, the main technical schemes compared in the full life cycle dimension are as follows:

1. Single-column tower (or A-type tower) + ordinary steel box girder + concrete cable tower + T-type pier + parallel wire stay cable;
2. Single column tower (or A-type tower) + UHPC deck composite girder (or steel-UHPC composite girder) + concrete cable tower + T-type pier + parallel wire stay cables;
3. Single-column tower (or A-type tower) + ordinary steel box girder + steel concrete tower (or steel shell concrete cable tower) + T-type pier + parallel wire stay cable;
4. Single column tower (or A-type tower) + UHPC deck composite girder (or steel-UHPC composite girder) + steel concrete tower (or steel shell concrete cable tower) + T-type pier + parallel wire stay cables.

### 3. Determination of basic parameters of the project

#### 3.1. Cost calculation period and base year

According to the conclusion of the project feasibility study stage and the approval comments, combined with the national and regional economic and traffic planning and considering the service life demands of the owners, society and users for Huangmaohai Cross-sea Bridge, the designed service life of
Huangmaohai Cross-sea Bridge is 100 years.

“The Economic Evaluation Method of Highway Construction Project” points out that the economic evaluation period equals construction period plus forecast period after the highway is put into operation. In the life cycle cost calculation system of whole society, the main cost is construction cost over the construction period, while maintenance cost and user cost mainly occur over operation period. Combined with the feasibility study report of Huangmaohai Cross-sea Bridge and the convenience and feasibility of practical calculation, the life cycle cost analysis period of Huangmaohai Cross-sea Bridge is 100 years after its completion (the end of 2024), namely 2025-2124. At the same time, the calculation base year is determined to be the year 2025 when the Huangmaohai Cross-sea Bridge is completed and opened to traffic.

3.2. Cost discount rate
In the analysis of the full life cycle cost, P.D. CADY proposed a synthetic model considering the discount rate\(^3\). In addition, the effect of discount rate is considered in the optimization analysis of the full life cycle cost of transportation infrastructure.

Through the analysis of the influencing factors of the discount rate, the determination of the discount rate depends on two parameters, the social discount rate and the annual change rate of PPI. By comprehensively considering the relationship among the three factors, the calculation model of the cost discount rate is as follows:

\[
1 + i_{cl} = (1 + f_i)(1 + l_i)
\]

\[
l_i = \frac{i_{cl} - f_i}{1 + f_i}
\]

Where \(l_i\) is the cost discount rate, \(f_i\) is the annual change rate of PPI, and \(i_{cl}\) is the social discount rate. According to the value range of social discount rate and annual change rate of PPI, combined with the calculation model of discount rate, the discount rate in this paper can be determined within the range of 0.95%-6.93%. The discount rate of this project is 4%.

4. Life cycle cost estimation

4.1. Construction period costs
The highway project’s estimate budget or final accounts comprehensively contains all the costs involved in the construction period of the project, and is compiled by companies familiar with the construction project. Therefore, it can accurately reflect the expenditure of the highway engineering project over the construction period, and there is no need to carry out tedious calculation again. At present, the cost of Huangmaohai Cross-sea Bridge is estimated in the preliminary design stage, and the construction cost is based on the estimated results in the preliminary design stage.

4.2. Operation period costs
(1) Management costs
The management costs of the highway are mainly the cost by the management department, which is established to ensure the normal operation of the highway and provide safe and comfortable travel quality for the users. Through the analysis of the management mode of various highways, the management mode of Huangmaohai Cross-sea Bridge is determined as follows:

| Personnel type                      | Calculation basis                      | Total |
|-------------------------------------|----------------------------------------|-------|
| Leadership                          | 1 Chairman, 1 manager, 2 deputy managers | 4     |
| Engineering Technology Department   | 5 maintenance engineers, 5 testing engineers | 10    |
| Highways department                 | 250 people/km\(^2\), a total of 1.054 km\(^2\) | 263   |
| The ministry of charge              | 12 people/place, 2 places in total     | 24    |
| Information monitoring center | 5 people | 5 |
|-------------------------------|----------|---|
| Finance department           | 5 people | 5 |
| General affairs department   | 5 people | 5 |
| Total                         | 316      |   |

The salary of management staff is 100,000 yuan/(year·person), referring to the average salary level of the transportation industry in Guangdong Province. Taking the increase level of salary and benefits as well as inflation into consideration, the estimation of management cost is based on the management cost in the first year of operation, and the annual management cost increases at a rate of 3%-4% (3% in this paper). According to the expert survey, analysis of evaluation results and other domestic highway data, the salary of management staff accounts for about 70% of the management cost, and the other 30% is the management service cost. According to the discount rate of 4%, the value of the 100-year total cost is 2.908 billion yuan, and the main approach bridge and other projects will be apportioned proportionally.

(2) General maintenance costs

General maintenance costs include daily maintenance costs, maintenance costs of minor repair and daily testing costs. Most maintenance work is generally performed by maintenance workers.

According to the analysis of the investigation and evaluation results and the personnel setup of other bridge maintenance organizations in China, it is suggested that a total of 60 members of maintenance staff should be provided for Huangmaohai Cross-sea Bridge. The salary of maintenance workers is based on the salary level of Guangdong Province, which is suggested to be 60,000 yuan/(year·person). Thus the costs of maintenance workers are $60 \times 60,000 = 3.6$ million yuan/year. According to the expert survey, analysis of evaluation results and other domestic bridge data, the costs of maintenance materials and testing tools accounts for about 60% of the maintenance costs. The details are as follows.

| The cost categories | Annual cost (ten thousand yuan/year) | Percentage (%) |
|---------------------|-------------------------------------|-----------------|
| Maintenance personnel cost | 60 members of maintenance staff | 360 40 |
| | The average salary is 60,000 Yuan/person·year | |
| | Other maintenance costs | 240 | 60 |
| | Total maintenance costs | 600 | 100 |

Considering that the per capita salary and related expenses increases by 3% and the cost discount rate is 4%, the 100-year full life maintenance costs are 386 million yuan. The main approach bridge and other works will be apportioned proportionally.

(3) Specialized testing costs

When the bridge is in operation for a certain period of time, the structure performance will inevitably degrade (suffering from disasters or accidents like floods, drift, ship collision, earthquake, windstorm, fire and overweight vehicles, vehicles carrying dangerous goods, etc.). In order to verify the reliability of bridge components, professional testing staff with professional testing equipment is needed to examine the costs of bridge in detail.

The specialized testing costs include the specialized testing costs of non-replaceable components (such as main girder, tower, pier and foundation) and the specialized testing costs of replaceable components (such as cable, steel box girder coating, bridge deck pavement, expansion device, support and anti-collision guardrail). According to the characteristics of the bridges in this project, the expert survey and the existing project experience, the specialized testing costs of each bridge component are shown in Table 5.
Table 4 Specialized testing costs of bridge components

| Components | Cycle (year/time) | Unit price (10,000 yuan/time) |
|------------|------------------|--------------------------------|
| Non-replaceable components | | |
| Main girder | | |
| Steel-concrete composite box girder | 5 | 32 |
| Steel box girder | 5 | 35 |
| Tower | 6 | 30 |
| Pier | 6 | 30 |
| Foundation | 8 | 20 |
| Replaceable components | | |
| Cables | 6 | 32 |
| Steel bridge tower coating | 6 | 35 |
| Steel box girder coating | 6 | 15 |
| Bridge deck pavement | | |
| Ordinary asphalt concrete | 4 | 9 |
| Epoxy asphalt concrete | | 13 |
| Expansion device | 5 | 12 |
| Support | 5 | 4 |
| Safety facilities | 5 | 2 |

Considering that testing costs increase by 3% per year and the cost discount rate is 4%, the specific testing costs of each scheme are shown in Chapter 5.

(4) Repair costs

After a certain period of operation, the durability of the bridge structure will decrease. In order to restore its reliability and improve the performance of the bridge to an expected functional level, maintenance (including medium repair and replacement) must be carried out for the bridge when it reaches a specified critical state.

According to the characteristics of the bridge of Huangmaohai Cross-sea Bridge, the expert survey and the existing project experience, the repair costs of each bridge component are shown in the table below.

Table 5 Repair costs of bridge components

| Components | Repair cycle (year/time) | Unit price of repair (10,000 yuan/time) | Replacement cycle (year/time) | Unit price of replacement (10,000 yuan/time) |
|------------|--------------------------|----------------------------------------|-------------------------------|---------------------------------------------|
| Damage treatment of concrete components | | | | |
| Cables | 5 | 200 | 25 | 17855 |
| Steel box girder coating | 5 | 40 | 20 | 980 |
| Steel bridge tower coating | 5 | 80 | 20 | 1470 |
| Bridge deck pavement | | | | |
| Ordinary | 3 | 30 | 10 | 2572.5 |
| Epoxy | 5 | 300 | 15 | 15435 |
| Support | | | | |
| Basin-shaped rubber support | 5 | 3 | 25 | 20 |
| Steel support | 12 | 14 | 35 | 150 |
| Expansion device | 7 | 400 | 20 | 4600 |
| Safety facilities | 5 | 80 | 40 | 9307 |

Taking into account the 3% annual increase in testing costs and the 4% cost discount rate, the repair costs of each scheme are shown in Chapter 5.

(5) Insurance costs

Large-scale bridge engineering is characterized by complex technology, large number of participants, long time span and significant influence by natural conditions, etc., which makes the bridge face various risks from the aspects of technology and force majeure during operation. Considering that the risks
cannot be eliminated and avoided, and the bridge management company has limited ability to bear the loss of disaster, the bridge management company should transfer the risk to the insurance company to enhance the ability to face risks.

Since the insurance costs are comprehensive costs, it is considered in the base year of the bridge operation period and in no relationship with time value of money. Thus its calculation model is as follows:

\[ C_{bx} = C_{js} \times (r_1 + r_2 + \ldots + r_l) \]

Where \( C_{bx} \) is total insurance costs in the operation period, \( C_{js} \) is the costs in the construction period, and \( r_i \) is the rate of each type of insurance.

According to the insurance rate standard of common large-scale projects in China, combined with expert-level research opinions, the comprehensive insurance rate is thought to be 0.42%. The insurance costs of each scheme are shown in Chapter 5.

(6) User costs

User costs refer to the costs caused by traffic jam, reduced speed, vehicle detour, delay caused by detour, freight increase, traffic accidents and transportation goods damage and loss due to management, inspection, maintenance and repair.

The value of passenger time is calculated based on the predicted value of GDP per capita. The passenger time costs of work travel are different from those of non-work travel. Among the passengers of cars and buses, the number of work travel and non-work travel passengers both accounted for 50%. The passenger time value of non-work travel is set as half of the passenger time value of work travel. The time value of a truck driver is calculated according to the time value of a work travel passenger.

Freight time costs are the product of the value of goods in transit, the quantity of goods in transit and the delay time.

According to the Huangmaohai Cross-sea Bridge project, the user costs are mainly the costs of traffic detour and delay caused by detour in the road closure and maintenance of approach bridges during the operation period. According to the previous analysis, road closure and maintenance are estimated at the shortest time of 5 years.

According to the composition of the traffic and passenger flow of the project, road closure is set as 6 hours each time. Considering the time value of money, the passenger time costs and cargo transportation time costs of the 100-year full life cycle are 63.59 million and 172.158 million respectively. The main approach bridge and other works will be apportioned proportionally.

(7) Environmental impact costs

Environmental impact costs may be incurred by poor bridge management, or pollution to the surrounding environment due to noise, damage to the land, soil erosion, discharge of pollutants or waste into adjacent water or air during maintenance, inspection or repair of the bridge. These costs result from incremental damage that is much greater than the damage caused by a bridge system operated under normal conditions, and these environmental damages are often at the cost of society.

In this study, the percentage of the environmental impact costs in the construction period is used to estimate the environmental impact costs by means of investigation, analysis and expert discussion. For general concrete components, the percentage is 10%. In other cases, steel structure has less impact on the ecological environment than concrete structure. The larger the bridge span is, the smaller its influence on water flow and marine ecology is.

The environmental impact costs are related to the maintenance year. Theoretically, the time value of money should be considered when calculating the environmental impact costs. Since the calculation of the environmental impact costs is based on the construction period cost of the base year, the environmental impact costs are not discounted in calculation. The calculation results of each scheme are shown in Chapter 5.

4.3. Disposal costs

Disposal costs refer to the cost incurred when the bridge has been decommissioned or when partial or complete demolition is required. In many cases, only the superstructure of the bridge needs to be
removed, and the costs should be calculated according to different bridge types and the specific circumstances. The costs of bridge demolition is closely related to the costs in the construction period of the bridge. Therefore, the percentage of the demolition costs in the construction period is considered in this study to estimate the costs:

\[ C_{cc} = \frac{C_{js} x}{(1 + I)^N} \]

Where \( C_{cc} \) is the demolition costs (unit: ten thousand yuan), \( C_{js} \) is construction period costs (ten thousand yuan), \( x \) is the percentage of demolition costs in construction period, \( N \) is the service life of the bridge, and \( I \) is the discount rate.

According to the characteristics of Huangmaohai Cross-sea Bridge and the similar experience of existing projects, the percentage equals 3% when the proportion of concrete components is relatively large. When the proportion of concrete components is relatively small, the percentage is appropriately lowered. The main calculation results are shown in Chapter 5.

5. Full life cycle cost analysis and evaluation

5.1. Comparison and analysis of different technical schemes

The scheme names and numbers of the single-column tower, A-type tower and A-type torsion tower are shown in Table 7. The full life costs and their composition are shown in Fig. 8.

| NO. | Design scheme | NO. | Design scheme | NO. | Design scheme |
|-----|---------------|-----|---------------|-----|---------------|
| A1-1 | Ordinary steel box girder + concrete tower +T-type pier + parallel wire stay cable | A2-1 | Ordinary steel box girder + concrete tower +T-type pier + parallel wire stay cable | A3-1 | Ordinary steel box girder + concrete tower +T-type pier + parallel wire stay cable |
| A1-2 | UHPC deck composite girder + concrete tower +T-type pier + parallel wire stay cables | A2-2 | UHPC deck composite girder + concrete tower +T-type pier + parallel wire stay cables | A3-2 | UHPC deck composite girder + concrete tower +T-type pier + parallel wire stay cables |
| A1-3 | Steel-UHPC composite girder + concrete tower +T-type pier + parallel wire stay cable | A2-3 | Steel-UHPC composite girder + concrete tower +T-type pier + parallel wire stay cable | A3-3 | Steel-UHPC composite girder + concrete tower +T-type pier + parallel wire stay cable |
| A1-4 | Ordinary steel box girder + Steel concrete tower +T-type pier + parallel wire stay cable | A2-4 | Ordinary steel box girder + Steel concrete tower +T-type pier + parallel wire stay cable | A3-4 | Ordinary steel box girder + Steel concrete tower +T-type pier + parallel wire stay cable |
| A1-5 | Single column tower | A2-5 | A-type tower | A3-5 | A-type torsion tower |
| A1-6 | Steel-UHPC composite girder + steel concrete tower +T-type pier + parallel wire stay cable | A2-6 | Steel-UHPC composite girder + steel concrete tower +T-type pier + parallel wire stay cable | A3-6 | Steel-UHPC composite girder + steel concrete tower +T-type pier + parallel wire stay cable |
| A1-7 | Ordinary steel box girder + steel shell concrete tower +T-type pier + parallel wire stay cable | A2-7 | Ordinary steel box girder + steel shell concrete tower +T-type pier + parallel wire stay cable | A3-7 | Ordinary steel box girder + steel shell concrete tower +T-type pier + parallel wire stay cable |
| A1-8 | UHPC bridge deck composite beam + steel shell concrete tower +T-type pier + parallel wire stay cables | A2-8 | UHPC bridge deck composite beam + steel shell concrete tower +T-type pier + parallel wire stay cables | A3-8 | UHPC bridge deck composite beam + steel shell concrete tower +T-type pier + parallel wire stay cables |
| A1-9 | Steel-UHPC composite girder + steel shell concrete tower +T-type pier + parallel wire stay cable | A2-9 | Steel-UHPC composite girder + steel shell concrete tower +T-type pier + parallel wire stay cable | A3-9 | Steel-UHPC composite girder + steel shell concrete tower +T-type pier + parallel wire stay cable |
For the main bridges of Huangmaohai Cross-sea Bridge, according to the comparison and analysis of different technical schemes, it can be seen that the difference of the full life cycle costs’ among each technical scheme is within 8%. The maximum full life cycle costs scheme is “A-type torsion tower + ordinary steel box girder + steel shell concrete tower +T-type pier + parallel wire stay cable”, which is 5.7699278 billion yuan. The minimum full life cycle costs scheme is “A-type tower + Steel-UHPC composite girder + steel concrete tower +T-type pier + parallel wire stay cable”, which is 5.1857359 billion yuan.

5.2 Comparison and analysis of different technical schemes
Taking the recommended schemes as examples, the analysis of the proportion of costs are as follows.

| Cost-type                  | Main bridges | Cost value (ten thousand yuan) | Percentage (%) |
|----------------------------|--------------|--------------------------------|----------------|
| Construction period costs  | Management costs | 73486.75                        | 13.08%         |
|                            | Maintenance costs | 9754.43                         | 1.74%          |
|                            | Testing costs | 1300.78                         | 0.23%          |
|                            | Repair costs | 93070.00                        | 16.56%         |
|                            | Insurance costs | 1451.52                         | 0.26%          |
|                            | User costs | 5957.48                         | 1.06%          |
|                            | Environmental impact costs | 31104.00                     | 5.54%          |
| Disposal costs             | 205.29                   | 0.04%                          |
| Total                     | 561930.25            | 100.00%                        |

As is can be seen from the above table, for the main bridges, the costs during construction period only accounts for a little more than 60% of the costs during the full life cycle, while the costs during operation period accounts for nearly 40%. This means that it is unreasonable to judge the quality of the project by using the traditional engineering cost method that only estimates the costs during the construction period and ignores the costs during the operation period. When evaluating the merits and demerits of highway projects, we should not only consider the construction period costs. Instead, we should focus on the full life cycle costs to judge whether the costs of highway projects are the most reasonable, both economically and technologically.

6. Conclusions and Suggestions
(1) The costs during the full life cycle of the bridge shall take into account costs of construction,
management and maintenance from the beginning of planning and design to the end of life and disposal, as well as the additional costs paid by the users and the society during the construction, operation and maintenance of the bridge, which include construction period costs, operation period costs (including management costs, maintenance costs, specialized testing costs, repair costs, user costs, environmental impact costs and insurance costs) and disposal costs in China.

(2) According to the characteristics of the maintenance costs of bridge components, they are divided into non-replaceable components and replaceable components. By determining the possible management, maintenance and maintenance time of the main components of the bridge and their corresponding costs parameters, the costs during the operation period can be figured out and the costs during the full life cycle of the bridge can be finally obtained.

(3) The analysis and calculation of the full life cycle costs of Huangmaohai Cross-sea Bridge need to be based on the forecast of the time of future testing, maintenance, repair, replacement and their corresponding costs. At the same time, limited to the lack of existing management, maintenance and repair data, part of the costs calculation has been simplified in the analysis and calculation of the full life cycle costs.

(4) Discount rate is one of the most sensitive parameters in the calculation of the full life cycle costs of a bridge. It is necessary to determine an appropriate discount rate to analyze and compare the costs of detection, maintenance, repair, replacement, disposal, recovery and reuse by discounting the cost into the net present value, so as to optimize the costs of bridge design scheme. The analysis period of Huangmaohai Cross-sea Bridge is 100 years. Based on the results of domestic research on the value of social discount rate and annual change rate of PPI, and combined with the calculation model of discount rate, the discount rate \( i \) over 100 years is within the range of 0.95%~6.93% in this paper.

(5) According to the expert survey, the basic parameters such as management costs and maintenance cost, specialized testing costs and repair costs for the bridge are determined. For the main bridges, the recommended scheme is “single column tower + ordinary steel box girder + concrete tower + T-type pier + parallel wire stay cable”. The difference between the full life cycle costs of the recommended scheme and others is within 8%. Although its costs are not the lowest, it has a good landscape effect.

(6) The costs during construction period accounts for about 60% of the costs during the full life cycle, while the costs during operation period accounts for nearly 40%. The main reason is that the thoughts of full life cycle design has already been introduced in the design of Huangmaohai Cross-sea Bridge. Besides, the durability design and necessary structural measures for inspection, maintenance and replacement are carried out in the design process.

(7) It is suggested that the initial construction period costs be appropriately increased, especially the durability design costs and the costs of the inspection, maintenance and replaceable measures, which can greatly reduce the operation period costs of the bridge, thus achieving the reduction of the full life cycle costs of the bridge.

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