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Study on economic performances of multi-span suspension bridges part 2: parametric study

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Abstract. Economic performances of consecutive multi-span suspension bridges are studied. The material amount and cost estimation formulas of the bridges have been derived in the part 1 of the study. A parametric study is carried out based on the formulas for investigating the different factors' effect on the bridge cost. The factors include the bridge sag, the bridge span, the bridge foundation and the environment condition, etc. Then, an economical layout of the bridges is proposed for different conditions. Lastly, a selection of suspension bridge types is discussed based on the economy of bridges.

Keywords: multi-span suspension bridge; economic performance; economical layout; cost estimation formula

1. Introduction

The construction of bridges crossing straits has been favored by authorities for reducing higher traffic pressures of air transports and navigations caused by global businesses and communications increasing for recent years. At last 4 projects have been completed since 1990s: Great Belt Bridges (Danish) in 1998, Oresund Link (Danish) in 2000, Hangzhou Bay Bridges (China) in 2008 and Qingdao Bay Bridges (China) in 2011. Besides, some larger projects are to be constructed in Fehmarn Belt, Taiwan Strait, Qiongzhou Strait and Gibraltar strait, etc. in the near future (Ge and Xiang 2006, 2008a, b, 2011, Gimsing 2009). In these projects, consecutive multi-span suspension bridges are recognized as a valid alternative to the ultra-long span length bridges only having one main span, e.g., typical suspension bridges and cable-stayed bridges, or these bridges connecting in series (Starossek 1996, Virlogeux 1999, Buckland and Matson 2006, Clemente *et al*. 2000, Kitagawa *et al*. 2001, Svensson 2007, Tang 2007, Sun *et al*. 2010, Yoshimura and Kawahara 2010, Zhang *et al*. 2011a, b, Zhang and Xiao 2011c).

There are some studies focusing on multi-span suspension bridges to be conducted for many years, such as: the deflection theory of multi-span suspension bridges considering the deflection of

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towers (Sato 1971); the analytical method used to calculate the structural natural frequency and the mode shape as well as the dynamic response (Hayashikawa and Watanabe 1982); the static stability (Nazir 1986); the analysis of multi-span suspension bridges with very long span up to 2000m (Fosberp 2001, Yoshida *et al*. 2004); the analysis for double main bridges constructed or at design stage, e.g., the Jiangsu Taizhou Bridge over Yangtze River with double main-span of 2×1080m completed in 2012, the Anhui Maanshan Bridge over Yangze River at design stage and the New Millennium Grand Bridge in Korea at design stage (Choi *et al*. 2010, Daniel *et al*. 2010, Forsberg 2001, Ge and Xiang 2006, 2008a, b, 2011, Jung *et al*. 2010, Luo *et al*. 2011); the aerodynamic flutter analysis of a new suspension bridge with double main spans (Zhang *et al*. 2011); and the simple analytical formulas calculating suspension bridges with double main cables in the vertical plan (Zhang *et al*. 2012), etc. Besides, the simple analytical formulas and parametric analysis for multi-span suspension bridges have been derived and completed in other studies of the author for investigating its mechanical performance.

Another key to construct a multi-span suspension bridge crossing a strait, however, is how to define a reasonable layout for obtaining the best economic performance besides the best mechanical performance, the construction having huge quantities. Unfortunately, there are few studies expect for the work of only assessing material requirements of the superstructure of traditional cable-stayed bridges and suspension bridges by Gimsing (2012) and Lewis (2012). Thus, some researches on the economic performance of multi-span suspension bridge are carried out in this study. In the part 1 of the study, the cost estimation formulas have been derived based on the structural ultimate carrying capacity. In this part, a parametric study is carried out for investigating the effect of factors, such as the bridge sag and the bridge span, on the bridge cost by the formulas. Then, an economical layout of multi-span suspension bridges and a selection of bridge types having cheaper cost are proposed and discussed for different environment conditions.

2. Cost formulas

The cost formulas in Part 1 are repeated for readers to well understand the data figures in the following and use the formulas conveniently. The cost of a suspension bridge is expressed in Eq. (1).

$$C = C_{sus} + C_{tow} + C_{arc} + C_{base} + C_{gir} \tag{1}$$

where C is the cost of the suspension bridge; C_{sus} is the cost of suspension systems; C_{tow} is the cost of towers; C_{arc} is the cost of anchorages; C_{base} is the cost of foundations; and C_{gir} is the cost of girders.

2.1 Cost of suspension system

The cost of suspension systems C_{sus} is expressed in Eq. (2).

$$C_{sus} = n_{mc}\mu_c Q_{mc} + n_{mc}\mu_r Q_{rm} + \mu_c Q_{sc} + \mu_r Q_{rs} \tag{2}$$

where n_{mc} is the numbers of main spans; Q_{mc} is the cable material consumption of a main span; Q_{rm} is the suspender material consumption of the main span; Q_{sc} is the cable material consumption of side spans; Q_{rs} is the suspender material consumption of side spans; and μ_c and μ_r is the unit cost of cables and suspenders respectively.

As for Q_{mc}, it is expressed as

$$Q_{mc} = A_{mc}\gamma_c S_{mc} \tag{3}$$

where A_{mc} is the cross section area of the main span cable, γ_c is the cable volume weight, and S_{mc} is the curve length of the cable.

A_{mc} and S_{mc} are expressed in Eqs. (4) and (5) respectively.

$$A_{mc} = \frac{(g_b + p + g_r) l_m \sqrt{l_m^2 + 16 f_m^2}}{8\sigma_c f_m - \gamma_c l_m \sqrt{l_m^2 + 16 f_m^2}} \tag{4}$$

$$S_{mc} = \frac{l_m}{2}\left\{ \left[1 + 16\left(\frac{f_m}{l_m}\right)^2\right]^{\frac{1}{2}} + \frac{\ln\left[\frac{4f_m}{l_m} + \left[1 + 16\left(\frac{f_m}{l_m}\right)^2\right]^{\frac{1}{2}}\right]}{\frac{4f_m}{l_m}} \right\} \tag{5}$$

where l_m is the main span length, f_m is the cable sag, p is the live load on the main span, g_b is the girder weight on the main span, g_r is the uniformly distributed weight of the suspenders at the main span, and σ_c is the cable tensile strength.

g_r is expressed as

$$g_r = \frac{\gamma_r}{\sigma_r - \left(\frac{1}{3} f_m + l_{rm}\right)\gamma_r}(g_b + p)\left(\frac{1}{3} f_m + l_{rm}\right) \tag{6}$$

where γ_r is the suspender volume weight, and σ_r is the suspender tensile strength.

As for Q_{sc}, it is expressed in Eq. (7)

$$\begin{cases} Q_{sc} = 2\gamma_c A_{mc} S_{sc} \\ S_{sc} = \frac{l}{4n_s}\left\{ a\sqrt{a^2+1} - b\sqrt{b^2+1} + \ln\frac{a + \sqrt{a^2+1}}{b + \sqrt{b^2+1}} \right\} \\ n_s = 4 f_a / l_s ,\, a = (h_b + 4 f_a)/l_s ,\, b = (h_b - 4 f_a)/l_s \end{cases} \tag{7}$$

where f_a is a side span cable sag, l_s is the side span length, and h_b is the tower height above the pavement.

As for Q_{rm} and Q_{rs}, these are expressed in Eqs. (8) and (9) respectively

$$Q_{rm} = \gamma_r (g_b + p + g_r)\left(l_{rm} + \frac{f_m}{3}\right) l_m \Big/ \sigma_r \tag{8}$$

$$\begin{cases} Q_{rs} = \frac{(g_{sr} + g_b + p)}{\sigma_r}\gamma_r\left(h_b l_s - \frac{4}{3} f_a l_s\right) \\ g_{sr} = \left(\frac{h_b}{2} - \frac{2}{3} f_a\right)(g_b + p)\gamma_r \Big/ \left[\sigma_r - \left(\frac{h_b}{2} - \frac{2}{3} f_a\right)\gamma_r\right] \end{cases} \tag{9}$$

where l_{rm} is the mid-span suspender length.

2.2 Cost of tower and girder

The cost of tower is expressed in Eq. (10).

$$C_{tow} = 2\mu_t Q_{st} + (n_{mc} - 1)\mu_t Q_{mt} \tag{10}$$

Where μ_t is the unit cost of the towers, Q_{mt} is the material consumption of a main-span tower, and Q_{st} is the material consumption of a side-span tower.

As for Q_{mt} and Q_{st}, these are expressed in Eq. (11)

$$\begin{cases} Q_{mt} = 8\dfrac{H_m f_m}{l_m}\left\{\exp\left[\dfrac{\gamma_t}{\sigma_t}h_t\right]-1\right\} \\ Q_{st} = H_m\left(\dfrac{4f_m}{l_m}+\dfrac{h_b+4f_a}{l_s}\right)\left\{\exp\left[\dfrac{\gamma_t}{\sigma_t}h_t\right]-1\right\} \end{cases} \tag{11}$$

where σ_t is the compressive strength of the towers, γ_t is the volume weight of the towers, h_t is the height of a tower, and H_m is the horizontal force of the cable connecting with the tower.

H_m is expressed as

$$H_m = \frac{(p + g_r + g_b + A_{mc}\gamma_c)l_m^2}{8f_m} \tag{12}$$

The cost of girders is expressed in Eq. (13)

$$\begin{cases} C_{gir} = \mu_g Q_{gir} \\ Q_{gir} = Lg_b \end{cases} \tag{13}$$

where L is the length of the girders.

2.3 Cost of anchorages

The cost of anchorages is expressed in Eq. (14)

$$C_{arc} = 2\mu_{sa}Q_{sa} + (n_{mc} - 1)C_{ma} \tag{14}$$

where μ_{sa} is the unit cost of a side-span anchorage; Q_{sa} is the material consumption of a side-span anchorage; and C_{ma} is the cost of a shared anchorage which is shared by two adjacent bridges only in the case of several typical suspension bridge connecting in series.

As for Q_{sa}, it is expressed in Eq. (15).

$$Q_{sa} = H_m(2/\mu_{arc} + \tan\alpha) \tag{15}$$

where μ_{arc} is the friction coefficient between the side-span anchorage and the ground, and α is the inclination chord angle of the cable connecting with the anchorage.

As for C_{ma}, it is expressed in Eq. (16).

$$C_{ma} = \mu_{ma1} Q_{ma1} + \mu_{ma2} Q_{ma2} \tag{16}$$

where μ_{ma1} is the unit cost of constructing the part above water, μ_{ma2} is the unit cost of constructing the part below water, Q_{ma1} is the anchorage material consumption of the part above water, and Q_{ma2} is the anchorage material consumption of the part below water.

Q_{ma1} and Q_{ma2} are expressed in Eqs. (17) and (18) respectively.

$$\begin{cases} Q_{ma1} = 2\left(\dfrac{H_q}{\mu_{arc}} + V_{sc}\right) \\ V_{sc} = H_m \tan\alpha, H_p = \dfrac{pl_m^2}{8f_m} \end{cases} \tag{17}$$

$$Q_{ma2} = \frac{N_{a1}}{\sigma_{a1}}\sigma_{a2}\left\{\exp\left[\frac{\gamma_{a2}}{\sigma_{a2}}\left(h_w + h_{so}\right)\right] - 1\right\} - \frac{N_{a1}}{\sigma_{a1}}\gamma_{a2}\left(h_w + h_{so}\right) + \frac{N_{a1}}{\sigma_{a2}}\gamma_{a2}\left(h_w + h_{so}\right) \tag{18}$$

where N_{a1} is the compression from the above-water part, and it equals Q_{ma1}; γ_{a2} is the caisson volume weight; σ_{a1} is the compressive strength of the anchorage above water; σ_{a2} is the compressive strength of the part below water; h_w is the water depth; and h_{so} is the thickness of the soil layer.

2.4 Cost of substructure

Three foundations are considered that include bored piles, concrete caissons and floating systems. The substructure cost is expressed in Eq. (19).

$$C_{base} = n_{base} C_{bpb}, \quad n_{base} C_{ccb} \quad \text{or} \quad n_{base} C_{flf} \tag{19}$$

where n_{base} is the numbers of foundations; and C_{bpb}, C_{ccb} and C_{flf} is the cost of a bored pile, a concrete caisson and a floating system respectively.
As for C_{bpb}, it is expressed in Eq. (20)

$$C_{bpb} = \mu_{bp} Q_{bp} + \mu_{bpi} n_{bp} Q_{bpi} \tag{20}$$

where Q_{bp} is the material consumption of a pile cap; Q_{bpi} is the material consumption of a pile; n_{bp} is the numbers of the pile; μ_{bp} and μ_{bpi} are the unit cost of the pile cap and the pile respectively.

n_{bp} is expressed in Eq. (21)

$$n_{bp} = \frac{N_{t2} + Q_{bp}}{A_{bpi}\sigma_{bpi}} \tag{21}$$

where N_{t2} is the compression from the tower bottom; σ_{bpi} is the compressive strength of the pile; and A_{bpi} is the section area of the pile, and it equals $1.96\pi\text{m}^2$.

As for Q_{bp}, it is expressed as

$$\begin{cases} Q_{bp} = C_{bpa} C_{bph} \gamma_{bp} A_{t2}^2 \\ A_{t2} = N_{t2} / \sigma_t \end{cases} \tag{22}$$

where γ_{bp} is the volume-weight of the pile cap; and C_{bpa} and C_{bph} are the coefficient of the pile cap section area and thickness to A_{t2}, which equal about 11 and about 0.8 respectively.

As for Q_{bpi}, it is expressed as

$$Q_{bpi} = A_{bpi}\gamma_{bpi}h_{sp} \tag{23}$$

where γ_{bpi} is the volume- weight of the pile, and h_{sp} is the length of the pile.

h_{sp} is expressed in Eq. (24)

$$\begin{cases} h_{sp} = h_{spw} + h_{sps} \\ h_{sps} = \dfrac{A_{bpi}\left(\sigma_{bpi} + \gamma_{bpi}h_{spw} - q_{sr}\right)}{D_{bpi}\pi q_{sk} - A_{bpi}\gamma_{bpi}} \end{cases} \tag{24}$$

where h_{spw} is the pile length in water, and it equals water depth; h_{sps} is the pile length in soil, and it equals soil thickness if it is larger than soil thickness; D_{spi} is the pile diameter; and q_{sk} and q_{sr} is the soil side friction and the soil bearing capacity respectively.

As for the cost of a concrete caisson foundation, it is expressed in Eq. (25).

$$C_{ccb} = \mu_{tp}Q_{tp} + \mu_{ca}Q_{ca} \tag{25}$$

where μ_{tp} is the unit cost of a tower pedestal, μ_{ca} is the unit cost of a caisson, Q_{tp} is the material consumption of the tower pedestal, and Q_{ca} is the material consumption of the concrete caisson.

Q_{tp} is expressed in Eq. (26).

$$Q_{tp} = \frac{A_{tpt} + A_{tpb}}{2}h_{tp}\gamma_{tp} \tag{26}$$

where h_{tp} is the height of the tower pedestal; γ_{tp} is the volume-weight of the tower pedestal; and A_{tpt} and A_{tpb} is the section area on the tower pedestal top and on the tower pedestal bottom respectively.

h_{tp}, A_{tpt} and A_{tpb} are expressed in Eq. (27).

$$\begin{cases} A_{tpt} = C_{tpt}A_{t2} \\ A_{tpb} = C_{tpb}A_{t2} \\ h_{tp} = C_{tph}A_{t2} \end{cases} \tag{27}$$

where C_{tpt}, C_{tpb} and C_{tph} is the ratio coefficient of the pedestal top section area, the pedestal bottom section area and the pedestal height to the tower bottom section area A_{t2}, which equals 4.92, 6.332 and 0.141 respectively.

As for Q_{ca}, it is expressed as

$$Q_{ca} = A_{cat}\sigma_{ca}\left\{\exp\left[\frac{\gamma_{ca}}{\sigma_{ca}}\left(h_w + h_{so}\right)\right] - 1\right\} - A_{cat}\gamma_{ca}\left(h_w + h_{so}\right) + N_{bs}\frac{\gamma_{ca}}{\sigma_{ca}}\left(h_w + h_{so}\right) \tag{28}$$

where A_{cat} is the section area on the caisson top, σ_{ca} is the compressive strength of the caisson, γ_{ca} is the volume-weight of the caisson, and N_{bs} is the compression from the tower and the tower pedestal.

A_{cat} and N_{bs} are expressed in Eqs. (29) and (30), respectively.

$$A_{cat} = C_{cat} A_{tpb} \tag{29}$$

$$N_{bs} = N_{t2} + N_{tp} \tag{30}$$

where C_{cat} is the ratio coefficient of the section area on the caisson top to the area on the tower pedestal bottom, and it equals about 2.48; and N_{tp} is the compression from the tower pedestal, and it equals its weight Q_{tp}.

As for the cost of a floating system, it is expressed as

$$C_{flf} = \mu_{fl} Q_{fl} + 4\mu_{cab} Q_{cab} + 4\mu_{sa} Q_{sa} + \mu_{tp} Q_{tp} \tag{31}$$

where μ_{fl} is the unit cost of a floating box, μ_{cab} is the unit cost of a cable, μ_{sa} is the unit cost of a suction anchor, Q_{cab} is the material consumption of the cable, Q_{fl} is the material consumption of the floating box, and Q_{sa} is the material consumption of the suction anchor.

Q_{fl}, Q_{cab} and Q_{sa} are expressed in Eq. (32)

$$\begin{cases} Q_{fl} = C_{Wfl} N_{bs} \\ Q_{cab} = \dfrac{N_{cab}}{\sigma_{cab}} \gamma_{cab} h_{ca} \\ Q_{sa} = V_{sa} \gamma_{sa} \\ V_{sa} = \dfrac{D_{sao}^2}{4} \pi t_{sa} + \dfrac{t_{sa}\left(D_{sao} + D_{sai}\right)}{2} \pi h_{sa} \end{cases} \tag{32}$$

where γ_{cab} is the volume-weight of the cable; σ_{cab} is the tension strength of the cable; h_{ca} is the length of the cable connecting the floating box and the suction anchor; γ_{sa} is the volume-weight of the suction anchor; C_{Wfl} is the ratio coefficient of the floating box weight to N_{bs}; t_{sa} is the wall thickness of the suction anchor, and it equals 50mm; h_{sa} is the height of the suction anchor; and D_{sao} and D_{sai} are the outside diameter and inside diameter of the suction anchor respectively.

D_{sao} and D_{sai} are expressed in Eq. (33).

$$\begin{cases} D_{sao} = \dfrac{\sqrt{16\left(\pi q_{sk} h_{sa}\right)^2 + 4N_{cab} \rho_w g h_w \pi} - 4\pi q_{sk} h_{sa}}{\rho_w g h_w \pi} \\ D_{sai} = D_{sao} - 2t_{sa} \end{cases} \tag{33}$$

where g is gravity acceleration, and ρ_w is water density.

As for h_{as}, it is expressed in Eq. (34) if it smaller than soil thickness, if not, it equals soil thickness.

$$h_{sa} = \sqrt{N_{cab} \Big/ \left(2C_{sah} \pi q_{sk} + \frac{C_{sah}^2}{4} \rho_w g h_w \pi\right)} \tag{34}$$

where C_{sah} is the ratio coefficient of the suction anchor height to the outside diameter, and it equals 8.

Table 1 Basic parameters

Parameters	Contents	Values
l_m	Main span length	1000m
l_s	Side span length	200m
f_m	Cable sag	100m
l_{rm}	Midspan suspender length	1m
h_b	Tower height above pavement	101m
h_f	Tower height below pavement	70m
h_t	Tower height	171m
g_b	Unit weight of main cable	2.65×10^5N/m
p	Live load	3.91×10^4N/m
ρ_w	Water density	1.0×10^3kg/m^3
g	Acceleration of gravity	9.8N/kg
q_{sk}	Side friction of soil stratum	40kPa
q_{sr}	Bearing capacity of soil stratum	1600kPa

Table 2 Material parameters

Parameters	Contents	Values
γ_r, γ_c	Volume-weight of suspender and main cable	85 (kN/m^3)
γ_t	Volume-weight of bridge tower	26 (kN/m^3)
γ_{tp}	Volume-weight of tower pedestal	26 (kN/m^3)
σ_r	Tension strength of suspender	400 (MPa)
σ_c	Tension strength of main cable	668 (MPa)
σ_t	Compressive strength of bridge tower considering reduction of bending stress	13.44 (MPa)
σ_{a1}	Compressive strength of anchorage	18.4 (MPa)
γ_{a2}, γ_{ca}	Volume-weight of concrete caisson	26 (kN/m^3)
γ_{bp}, γ_{bpi}	Volume-weight of pile cap and bored pile	26 (kN/m^3)
σ_{bpi}	Compressive strength of bored pile	13.8 (MPa)
σ_{a2}, σ_{ca}	Compressive strength of concrete caisson	13.8 (MPa)

3. Basic parameters

The structural details of a suspension bridge are shown in Table 1 as the basic system in the study. Additionally, all of the main spans are assumed to be of equal parameters, and the soil stratum composed of the clay soil having plasticity index from 0.75 to 1 is adopted.

The material performance of the bridge materials is shown in Table 2.

The unit cost of the materials is shown in Table 3.

The unit cost of bored piles is shown in Table 4 when water depth is smaller than 20m.

For the case of water depth larger than20m, the unit cost of bored plies is expressed in Eq. (35).

$$U(h)=\exp\left[0.889\frac{h-100}{100}+0.711\right]U(20),\ h\geq 20\text{m} \tag{35}$$

where $U(h)$ is the unit cost of bored piles when water depth=h, $U(20)$ is the unit cost in a water depth of 20m.

The parameters of floating foundations are shown in Table 5.

Table 3 Unit cost of materials

Unit cost	Contents	Values
μ_c	Unit cost of main cable (including the cost of suspender)	2.41764×10^4￥/t (2.41764￥/N)
μ_r	Has been included in the cost of main cable	/
μ_{sa}	Unit cost of side-span anchorage (including the base under anchorage)	1.2×10^3￥/m^3 (0.046￥/N)
μ_{ma1}	Unit cost of anchorage shared by adjacent bridge (the part above water)	7.836×10^2￥/m^3 (0.03￥/N)
μ_t	Unit cost of bridge tower	2.2202×10^3￥/m^3 (0.0853￥/N)
μ_{ma2}, μ_{ca}	Unit cost of concrete caisson	8.727×10^2￥/m^3 (0.0335￥/N)
μ_g	Unit cost of girder	1.15522×10^4￥/t (1.15522￥/N)
μ_{bp}	Unit cost of bearing platform	7.671×10^2￥/m^3 (0.0295￥/N)

Table 4 Unit cost of bored pile (μ_{bpi})

Water depth (m)	0	3	5	10	20
Cost (￥/m^3)	1154	1632.4	1835.5	2132.6	2463.7

Table 5 Parameters about floating foundation

Parameters	Contents	Values
γ_{cab}	Volume-weight of cable in floating foundation	85 (kN/m^3)
γ_{sa}	Volume-weight of suction anchor	78 (kN/m^3)
σ_{cab}	Tension strength of cable in floating foundation	150 (MPa)
μ_{fl}	Unit cost of floating box	1.2×10^4 (￥/t)
μ_{cab}	Unit cost of cable	3.2×10^4 (￥/t)
μ_{sa}	Unit cost of suction anchor	1.0×10^4 (￥/t)

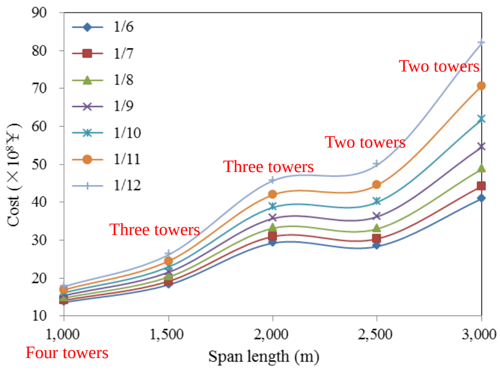
4. Parametric study

4.1 Cost of superstructure

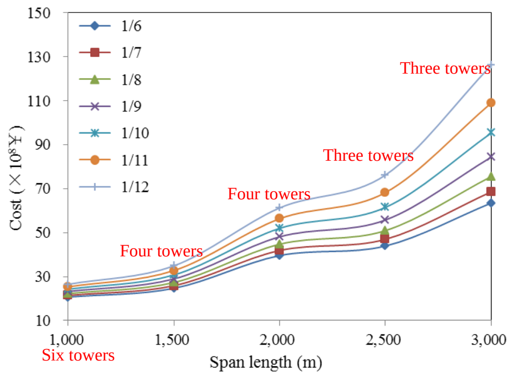
It is easier by dividing bridges into two parts: the superstructure and the substructure. Because the factors considered in analysis could be reduced.

For the superstructure, only cable sag and span length could affect its cost. Fig. 1(a) shows the relationship between the superstructure cost and span length with various cable sag ratios in the case of 3km wide water.

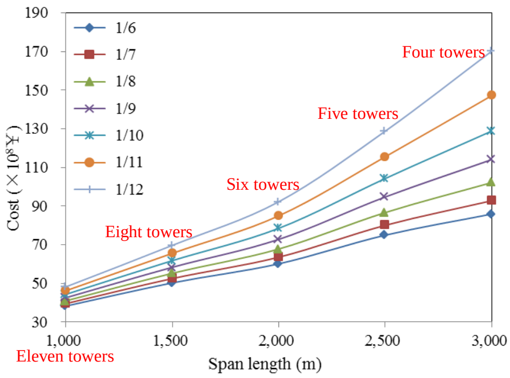
The zigzag increase of the cost is observed with span length increasing from Fig. 1(a). And the larger the cable sag, the lower the cost is, in the case of the same span length. This increase could be caused mostly by the span numbers varying with span length increasing. The varying could cause the girder having different total length which produces a disturbing on the increased



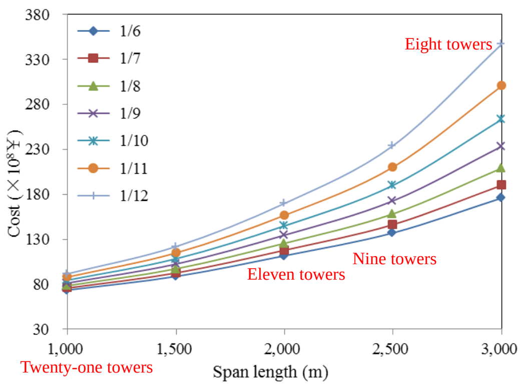
(a) 3km wide water



(b) 5km wide water



(c) 10km wide water

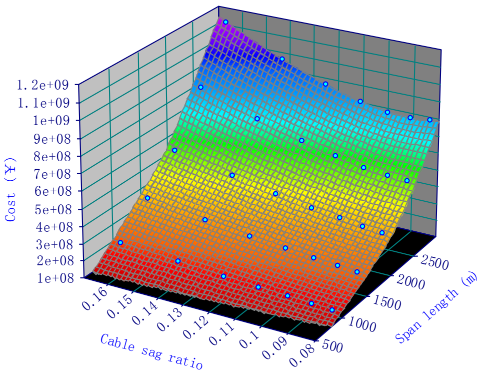


(d) 20km wide water

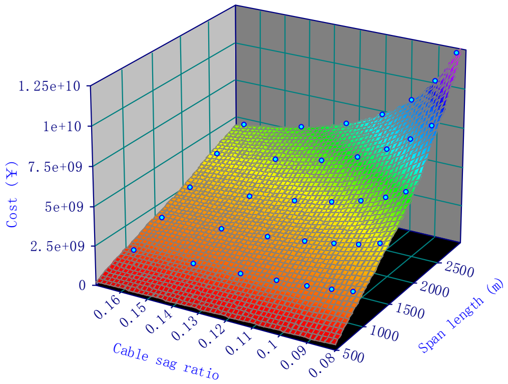
Fig. 1 Relationship between the superstructure and span length

tendency of the cost. However, the disturbing is decreasing with water length increasing, which can be observed from Figs. 1 (a)-(d). The cost curve in the in Figs. 1 (b)-(c) has smoother shape than the curve in Fig. 1(a). And, the cost curve in Fig. 1(d), in which the water width increases to 20km, tends to increase monotonically and acceleratedly with span length increasing. Additionally, the superstructure cost shows a decrease tendency, which isn't influenced by water width, with cable sag increasing.

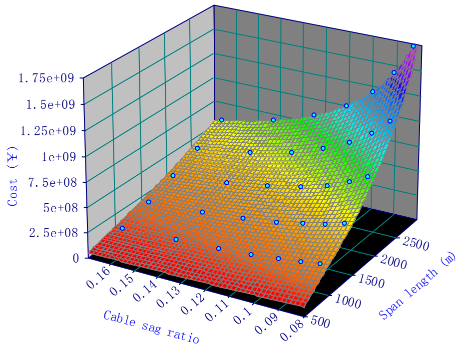
The cost of each member is offered in Figs. 2 (a)-(c) for understanding in more details. The cost of the cable and the anchorage shows an increased trend with span length increasing and cable sag decreasing. The cost of the tower, however, decreases with cable sag decreasing in the cable sag ratio region from about 1/6 to about 1/10, but becomes slightly increasing when the cable sag ratio is less than 1/10. These findings imply a possibility that the superstructure cost could be decreased as cable sag decreases if the tower cost is weighted. This possibility, however, occurs only in an ideal situation. Because the bridge tower have far less cost than cables unless it adopts extremely expensive materials and construction methods in generally.



(a) Tower



(b) Main cable



(c) Anchorage

Fig. 2 Cost of superstructure components (10km wide water)

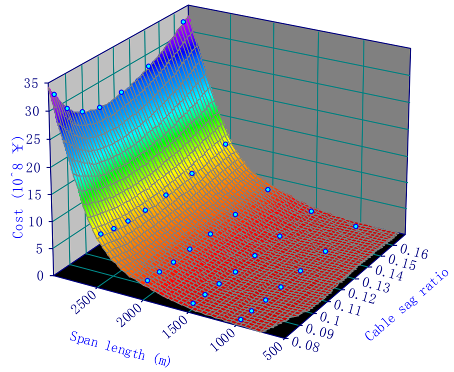
4.2 Cost of substructure

One bored pile foundation is analyzed prior as the representative case for facilitating the research of substructure economical performances. Figs. 3 (a)-(d) offer the relationship of span length, cable sag ratio and a bored pile cost under different water depth, respectively.

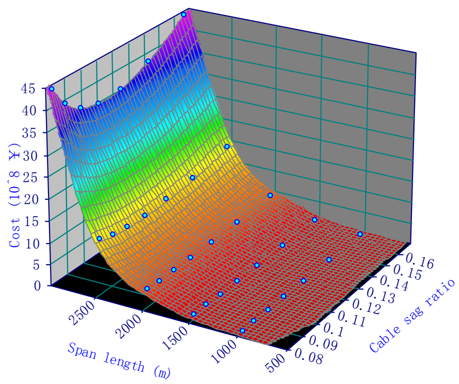
The finding, in each case of cable sag ratios, is that the cost of the bored pile increases with span length increasing. For the cost in each case of span lengths, however, it decreases and then turn to increases with cable sag ratio decreasing. And the value of the sag ratio in the cost curve turning point increases with span length increasing in the four figures. Besides, the four figures all show the similar relationship of span length, cable sag ratio and the cost, which indicate the slight effect of water depth on the relationship of the three factors.

This conclusion offers a clear justification that water depth and cable sag ratio could be isolated from each other when investigating their effect on the substructure cost. Thus, the parametric study for the cost of substructure only need consider foundation numbers and water depth.

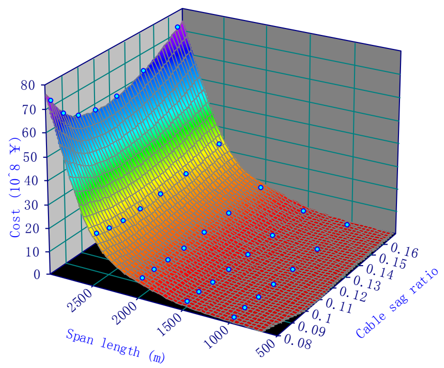
Fig. 4 shows their influence on the cost of all bored piles under different water widths, in which the increase of span length in X-axis represents the decrease of foundation numbers under a water width.



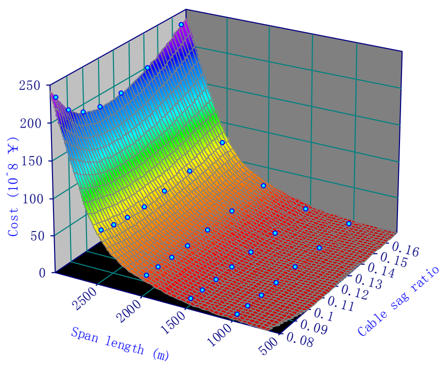
(a) 10m deep water



(b) 50m deep water

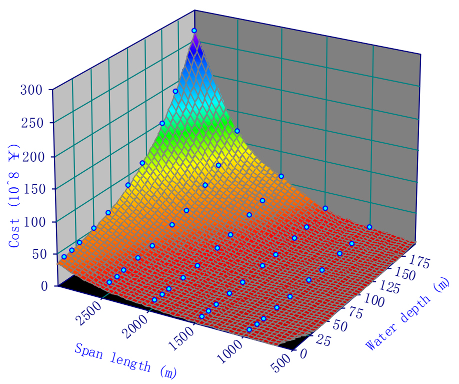


(c) 100m deep water

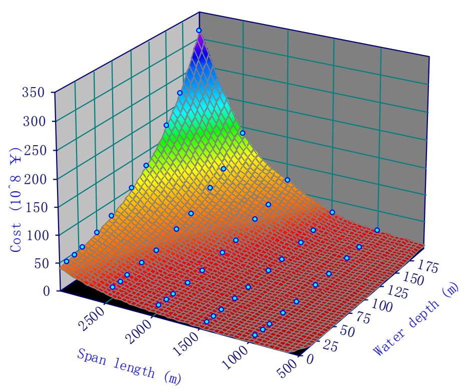


(d) 200m deep water

Fig. 3 Cost of one bored pile foundation

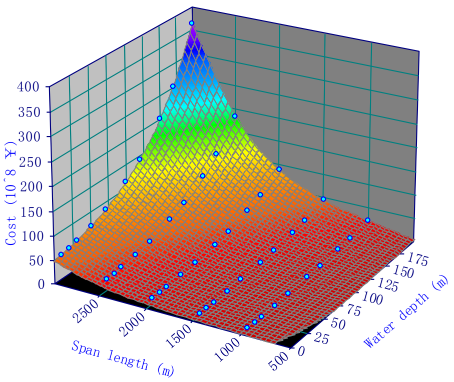


(a) 3km wide water

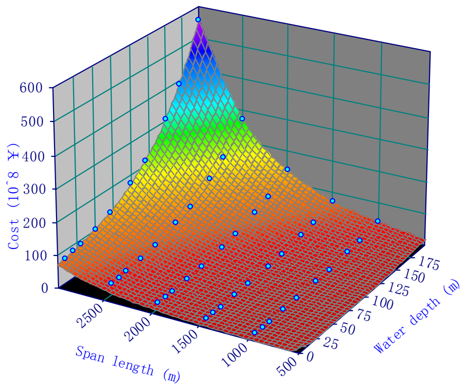


(b) 5km wide water

Fig. 4 Cost of all bored pile foundations (sag ratio of 1/10)



(c) 10km wide water



(d) 20km wide water

Fig. 4 Continued

The total cost presents a monotonic increase trend as water depth increases under different water widths, just as shown in Figs. 4 (a)-(d), because of the independence between water depth and foundation numbers. And the figures show the same development of the total cost increasing with span length increasing in the case of water widths of 3km, 5km, 10km and 20km.

This phenomenon could be interpreted by the relationship of foundation numbers and single foundation cost. It is observed from Fig. 3 that the increase of span length raises the cost of single foundation, but mean while reducing the numbers of foundations. Thus, the key of the substructure cost increasing with span length varying is whether the increase rate of single foundation cost is larger than the decrease rate of foundation numbers with span length increasing. It could be expressed as follows

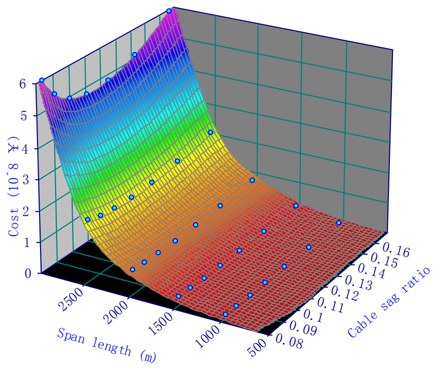
$$\frac{C_{l_1}}{C_{l_2}} > or < \frac{n_{l_2}}{n_{l_1}} \approx \frac{l_1}{l_2} \cdot \frac{L-2l_{s2}+l_2}{L-2l_{s1}+l_1} \tag{36}$$

where C_{l1} and C_{l2} is single foundation cost in the case of l_1 and l_2 span; n_{l1} and n_{l2} is foundation numbers under the two span lengths; L is water width; and ls_1 and ls_2 is the side span corresponding to l_1 and l_2. When C_{l1}/C_{l2} is smaller than n_{l1}/n_{l2}, the total cost with span length l_1 is lower than that with span length l_2, if not, it is higher than the cost with span length l_2. Actually, for the item of $(L\text{-}2l_{s2}+l_2)/(L\text{-}l_{s1}+l_1)$, it approximately equals 1 for wider water that means the ratio of foundation numbers could be replaced by the ratio of span length.

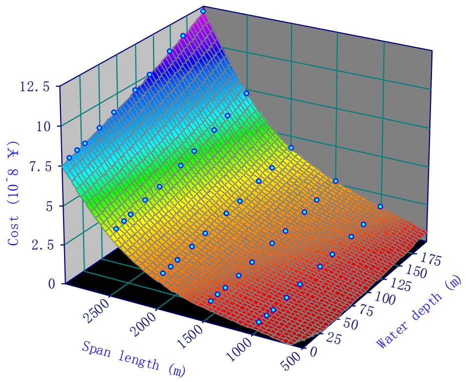
Figs. 5 (a)-(b) offer the per cost and the total cost of other foundations in the case of 10km wide water for investigating the effect of foundation types. The figures present a trend of the cost as similar as Fig. 3 and Fig. 4. This finding means that the parameter effect of superstructure and environment conditions on the substructure cost is independent of foundation types.

4.3 Total cost of the bridge

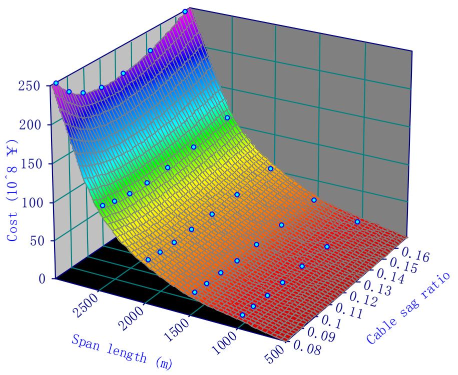
It is known from Section 4.1 and Section 4.2 that larger span length makes both the superstructure cost and the substructure cost higher. This causes the increased total cost of the



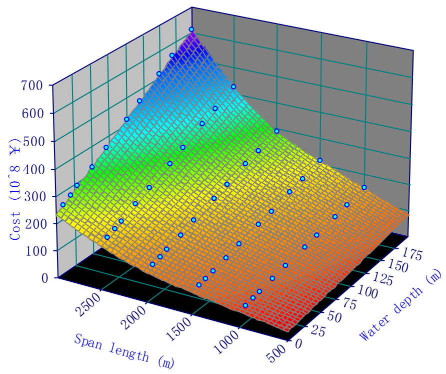
(a) Cost of one concrete caisson



(b) Total cost of concrete caissons



(c) Cost of one floating foundation



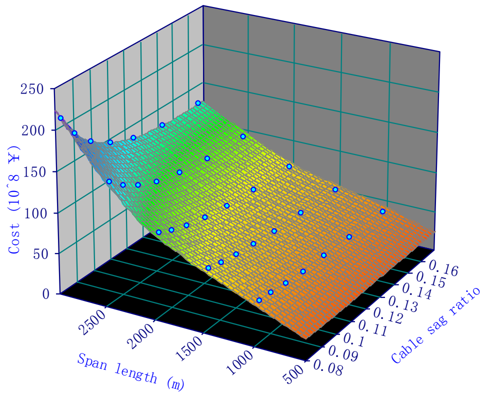
(d) Total cost of floating foundations

Fig. 5 Cost of other foundations

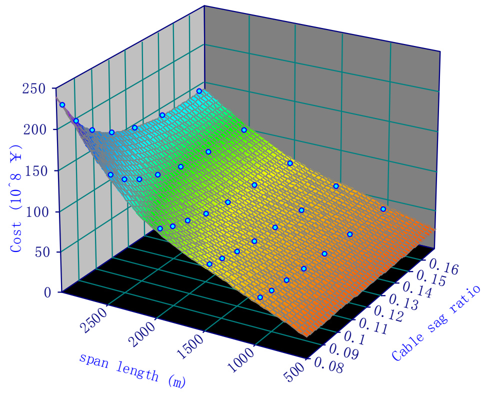
bridge with span length increasing regardless of other factors such as water depth and water width. Additionally, the conclusion that deeper water depth makes the total cost of the bridge higher also could be known from Section 4.1 and Section 4.2.

Thus, only the effect of cable sag on the bridge cost may be depended on other factors because of its different influences on the cost of the superstructure and the substructure. Figs. 6 (a)-(d) present the relationship of the bridge cost (adopting bored pile foundation) with different span lengths and cable sag ratios under the water depth from 10m to 200m.

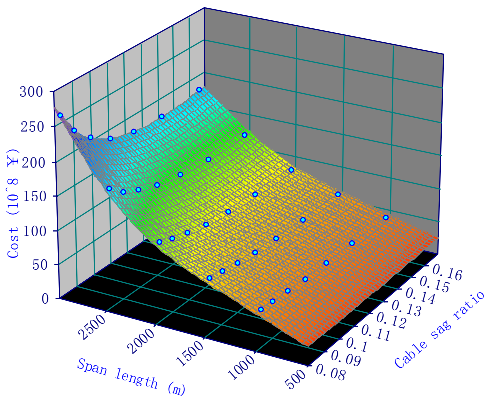
The different trend of bridge cost could be observed in the figures. The bridge cost all decreases with cable sag ratio increasing in Fig. 6(a) (10m deep water), but it becomes irregular in Fig. 6(d) (200m deep water) that decreases and turn to increases with cable sag ratio increasing. Besides, the effect of cable sag ratio is accelerated by increasing span length. This may be determined by the proportion of the superstructure cost and the substructure cost in the total cost. For Figs. 6 (a)-(c), the substructure cost is just under 50% percent of the total cost that causes the effect of cable sag ratio on bridge cost as similar as on the superstructure cost. For Fig. 6(d), however, the variation of the bridge cost follows a concave line due to the proportion of the substructure cost raised up to 50%~80%, just like the variation of the substructure cost shown in Fig. 5. It implies that the cheaper-cost may occur when the cable sag ratio equals a value decreasing in the region from 1/9 to 1/7 with water deepening if the substructure cost is larger than the superstructure cost. And the larger the substructure cost, the smaller the cable sag ratio of cheaper-cost occurring is.



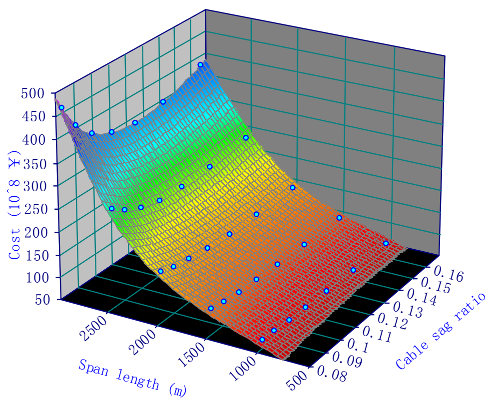
(a) 10m water depth



(b) 50m water depth



(c) 100m water depth



(d) 200m water depth

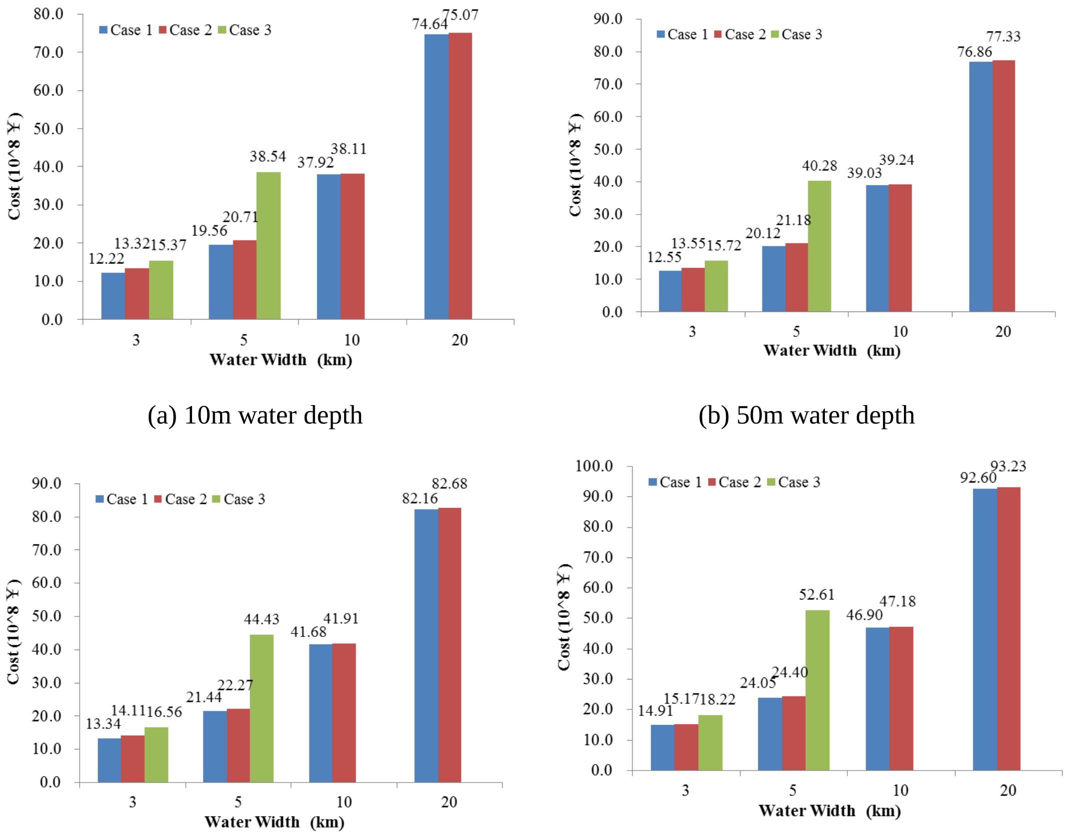
Fig. 6 Total cost of bridge

5. Selection and layout of bridges

One thing considered commonly in building bridges is how to define a better layout having cheaper cost especially for these large projects crossing straits and bays. A conclusion could be obtained from section 4 that a smaller span should be selected for cheaper consecutive multi-span suspension bridges. Besides, the cheaper cable sag ratio is the larger one but becomes the value in 1/9 to 1/7 if substructure has higher cost than superstructure, and it would decreases as the substructure cost increases.

Another thing worrying bridge engineers, however, is whether a long-span typical suspension bridge or a multi-span bridge consisting of several three-span bridges placed end to end, just as San Francisco Oakland Bay Bridge, is a cheaper choice than a consecutive multi-span suspension bridge.

Table 5 offers the cheapest scheme of bridges under different water depths when water width equals 3km, 5km, 10km and 20km. Their costs are shown in Fig. 7.



(a) 10m water depth

(b) 50m water depth

(c) 100m water depth

(d) 200m water depth

Fig. 7 Bridge cost under different depths

From Fig. 7, Case 3 always has the highest cost than other two cases under different water depths and widths, but the cost of Case 3 beyond other two cases increases with water widt increasing and decreases with water width decreasing. That implies the cost of constructing a typical suspension bridge with long-span is larger than the cost of constructing a multi-span bridge with the same total length at least when their main span is larger than 1000m. As for the case of a suspension bridge having span length smaller than 1000m, it is not studied because that it is commonly not a better choice compared to other bridges such as cable-stayed bridges and arch bridges.

Besides, the cost of Case 1 is smaller than that of Case 2 from Fig. 7. That indicates the cheaper cost of a consecutive multi-span suspension bridge than a multi-span suspension bridge consisting of several three-span bridges placed end to end. It is not only because that the latter costs more for each bridge tower due to the increasing of materials, but also because that the latter costs more for the additional shared anchorages compared with the former. Thus, a multi-span suspension bridge, which consists of several three-span bridges placed end to end, has higher cost of superstructure and substructure than a consecutive multi-span suspension bridge.

Table 5 The cheapest scheme of bridges

Cases	Bridge Types	Water Width (km)	Water Depth (m)	Side-span ratio	Main Span (m)	Cable Sag Ratio	Main Span Numbers	Cost (×10^8￥)
Case 1	The consecutive multi-span suspension bridge	3	10	0.5	1000	1/6	2	12.22
			50	0.5	1000	1/6	2	12.55
			100	0.5	1000	1/6	2	13.34
			200	0.5	1000	1/6	2	14.91
		5	10	0.5	1000	1/6	4	19.56
			50	0.5	1000	1/6	4	20.12
			100	0.5	1000	1/6	4	21.44
			200	0.5	1000	1/6	4	24.05
		10	10	0.5	1000	1/6	9	37.92
			50	0.5	1000	1/6	9	39.03
			100	0.5	1000	1/6	9	41.68
			200	0.5	1000	1/6	9	46.90
		20	10	0.5	1000	1/6	19	74.64
			50	0.5	1000	1/6	19	76.86
			100	0.5	1000	1/6	19	82.16
			200	0.5	1000	1/6	19	92.60
Case 2	The multi-span suspension bridge consisting of several three-span bridges placed end to end	3	10	0.5	1000	1/6	2	13.32
			50	0.5	1000	1/6	2	13.55
			100	0.5	1000	1/6	2	14.11
			200	0.5	1000	1/6	2	15.17
		5	10	0.5	1000	1/6	3	20.71
			50	0.5	1000	1/6	3	21.18
			100	0.5	1000	1/6	3	22.27
			200	0.5	1000	1/6	3	24.40
		10	10	0.5	1000	1/6	5	38.11
			50	0.5	1000	1/6	5	39.24
			100	0.5	1000	1/6	5	41.91
			200	0.5	1000	1/6	5	47.18
		20	10	0.5	1000	1/6	10	75.07
			50	0.5	1000	1/6	10	77.33
			100	0.5	1000	1/6	10	82.68
			200	0.5	1000	1/6	10	93.23
Case 3	The typical suspension bridge	3	10	0.5	1500	1/6	1	15.37
			50	0.5	1500	1/6	1	15.72
			100	0.5	1500	1/6	1	16.56
			200	0.5	1500	1/6	1	18.22
		5	10	0.5	2500	1/6	1	38.54
			50	0.5	2500	1/6	1	40.28
			100	0.5	2500	1/6	1	44.43
			200	0.5	2500	1/6	1	52.61

6. Conclusions

In this part of the study, the parametric study of the bridge cost is carried out. Some conclusions could be drawn as follows:

• For a consecutive multi-span suspension bridge with span more than 1000m, it could have cheaper cost when the main span equals 1000m and when the cable sag ratio equals 1/6. But, the cable sag ratio becomes the value in the region from 1/7 to 1/9 in the case of the substructure having larger cost than the superstructure, which decreases with the substructure cost increasing.

• For a suspension bridge with span more than 1000m, the typical suspension bridge with one main span and two towers is more expensive than the multi-span suspension bridge having the same total length.

• A multi-span suspension bridge consisting of several three-span bridges placed end to end is more expensive than a consecutive multi-span suspension bridge.

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References

Buckland, P.G. and Matson, D.D. (2006), "Increasing the load capacity of major bridges", *Proceeding of IABSE Symposium on Maintenance and Rehabilitation of Large Infrastructure Projects, Bridges and Tunnels*, Copenhagen, Denmark, January.

Clemente, P., Nicolosi, G. and Raithel, A. (2000), "Premliminary design of very long-span suspension bridges", *Eng. Struct.*, **22**, 1699-1706.

Choi, D.H., Na, H.S., Gwon, S.G., Yoo, D.H. and Moon, C. (2010), "A parametric study on the ultimate behaviors of multi-span suspension bridges", *Proceeding of 34th International Symposium on Bridge and Structural Engineering*, Venice, Italy, September.

Daniel, R.A., Dooren, F.J.V. and Meijer, R.H.D. (2010), "Comparison of a single and double main-span suspension bridge for the Western Scheldt crossing", *Proceeding of the 34th International Symposium on Bridge and Structural Engineering*, Venice, Italy, January.

Fosberp, T. (2001), "Multi-span Suspension Bridges", *Steel. Struct.*, **1**, 63-73.

Ge, Y.J. and Xiang, H.F. (2006), "Tomorrow's challenge in bridge span length", *Proceedings of IABSE Symposium on Responding to Tomorrow's Challenges in Structural Engineering*, Budapest, September.

Ge, Y.J. and Xiang, H.F. (2008a), "Aerodynamic challenges in long-span bridges", *Proceeding of IstructE centenary conference*, HongKong, China, January.

Ge, Y.J. and Xiang, H.F. (2008b), "Bridging capacity innovations on cable-supported bridges", *Proceeding of the 4th International Conference on Bridge Maintenance, Safety and Management*, Seoul, Korea, July.

Ge, Y.J. and Xiang, H.F. (2011), "Extension of bridging capacity of cable-supported bridges using double main-spans or twin parallel decks solutions", *Struct. Infras. Eng.*, **7**(7-8), 551-567.

Gimsing, N.J. (2012), *Cable Supported Bridges-Concept＆Design, Third Edition*, John Wiley＆Sons Ltd., Chichester.

Gimsing, N.J. (2009), "From bridges across Great Belt and Oresund towards a Femern Belt Bridge", *Proceeding of IABSE Symposium*, Shanghai, China, January.

Hayashikawa, T. and Watanabe, N. (1982), "Suspension bridge response to moving loads", *J. Eng. Mech. Div*., **108**(6). 1051-1066.

Jiang, H.X. (2010), "Study on structural systems in sea-crossing bridge of floating deep-water foundation", Ph.D. Dissertation, Tongji University, Shanghai, China. (in Chinese)

Jung, J., Kim, J., Baek, J. and Choi. H. (2010), "Practical design of continuous two main-span suspension bridge in Korea", *Proceeding of 34th International Symposium on Bridge and Structural Engineering*, Venice, Italy, September.

Kitagawa, M., Kashima, N., Fukunaga, S., Anzar, M.A.C.M. and Moriya, T. (2001), "Stability studies of ultra-long four span suspension bridge", *Proceeding of IABSE Conference on Cable-supported Bridges*, Seoul, Korea, August.

Lewis, W.J. (2012), "A mathematical model for assessment of material requirements for cable supported bridges: Implication for conceptual design", *Eng. Struct*., **42**, 266-277.

Luo, X.Y., Wang, D.L. and Chen, A.R. (2011), "The landscape design and form finding study of Taizhou Yangtze river highway bridge", *International Conference on Electric Technology and Civil Engineering*, Wuhan, China, April.

Nazir, C.P. (1986), "Multispan balanced suspension bridge", *J. Bridge. Eng.*, **110**(3), 392-404.

Recommended Practice for Planning (1997), *Designing and Constructing Tension Leg Platform*, American Petroleum Institute, Pennsylvania.

Recommended Practice for Planning (2000), *Designing and Constructing Fixed Offshore Platforms-Working Stress Design*, American Petroleum Institute, Pennsylvania.

Sato, K. (1971), "Deflection theory of multi-span suspension bridges considering deflection of towers and its numerical examples of various influence lines", *Proceedings of Japan Society Civil Engineering*, Japan. (in Japanese)

Starossek, U. (1996), "Cable-stayed bridge concept for longer spans", *J. Bridge. Eng*., **1**(3), 99-103.

Svensson, H. (2007), "The development of cable-stayed bridges since John Robling", *Proceeding of IABSE Symposium*, Weimar, Germany, January.

Sun, B., Chen, J. and Xiao, R.C. (2010), "Preliminary design and parametric study of 1400m partially earth-anchored cable-stayed bridge", *Sci. China Technol. Sci.*, **53**(2), 502-511.

Tang, M.C. (2007), "Evolution of bridge technology", *Proceeding of IABSE Symposium*, Weimar, Germany, January.

Virlogeux, M. (1999), "Recent evolution of cable-stayed bridges", *Eng. Struct*., **21**, 737-755.

Yoshida, O., Okuda, M. and Moriya, T. (2004), "Structural characteristics and applicability of four-span suspension bridge", *J. Bridge. Eng*., **9**(5), 453-463.

Yoshimura, T. and Kawahara, M. (2010), "Aerodynamic stability of large suspension bridge using cable frames", *Proceeding of the 34th International Symposium on Bridge and Structural Engineering*, Venice, Italy, January.

Zhang,W.M., Ge, Y.J. and Levitan, M.L. (2011), "Aerodynamic flutter analysis of a new suspension bridge with double main spans", *Wind Struct*., **14**(3), 187-208.

Zhang, L.W., Xiao, R.C. and Xia, R.J. (2011a), "Mechanical analysis and study on structural parameter of partially earth-anchored cable-stayed bridge part one: mechanical analysis", *Appl. Mech. Mater*., **44-47**, 1898-1905.

Zhang, L.W., Xiao, R.C. and Xia, R.J. (2011b), "Mechanical analysis and study on structural parameter of partially earth-anchored cable-stayed bridge part two: parametric study", *Appl. Mech .Mater*., **44-47**, 1906-1912.

Zhang, L.W. and Xia, R.J. (2011c), "The reasonable finished dead state research of partially earth-anchored cable-stayed bridge", *Adv. Mater. Res*., **255-260**, 1319-1325.

Zhang, L.W., Xiao, R.C., Jiang, Y. and Chai, S.B. (2012), "The characteristics of the multi-span suspension bridge with double main cables in the vertical plane", *Struct. Eng. Mech*., **42**(3), 291-311.