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NEW CABLE TENSION ADJUSTMENT METHOD FOR SUSPENDED-SPAN BRIDGE

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SUMMARY

This paper discusses the application of a new cable tension adjustment method for suspended-span bridges through the use of system identification (SI). Accurate error factor estimation is possible by the SI method. After successful application of the method, the structural computer model becomes identical to the proto-type bridge under static analysis.

As a result, the cable tension adjustment process can be shortened while maintaining proper quality control.

INTRODUCTION

Proper cable tension adjustment is one of the most important aspects in the construction of suspended-span bridges, such as cable-stayed bridges, suspension bridges and so on. The present authors previously presented the formulation of the SI method and a numerical example in reference [1]. This paper presents a practical application of the SI method, after a brief review of the formulation.

ERROR FACTOR ANALYSIS

It is very important to draw out error factors which are inherent in the construction of suspended-span bridges. Error factors may be divided into the following three categories: structural analysis errors, construction errors and fabrication errors[1]. A brief summary of the formulation[1] is given below.

Let {Z} be the error vector, the components of which consist of camber errors and member force errors.

{Z} can be written as a linear superposition of error modes as follows:

$$\{Z\} = \sum_{i=1}^{n} \alpha_i \{F_i\} \qquad (\{F_i\}: \text{ Error mode}) \tag{1}$$

In matrix form:

$$\{Z\} = [F]\cdot\{\alpha\} \tag{2}$$

where,

$$[F] = \begin{bmatrix} f_{11} & f_{12} \cdots\cdots & f_{1n} \\ f_{21} & f_{22} & \vdots \\ \vdots & \ddots & \vdots \\ f_{m1} & f_{m2} \cdots\cdots & f_{mn} \end{bmatrix}, \qquad \{\alpha\} = \begin{Bmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \\ \alpha_n \end{Bmatrix}$$

{Z} : Error vector
m : Index of field measurement items
n : Index of error factors
[F] : Error influence matrix
{α} : Error contribution rate vector

Assuming {R} to be field-measured values of cambers and member forces, and $\{R_o\}$ to be the corresponding calculated values obtained without an error model, {R} can then be written as follows:

$$\{R\} = \{R_o\} + \{Z\} \tag{3}$$

In reality, Eq. 3 is an approximation; therefore, Eq. 3 can be transformed into the following optimization problem.

$$\Phi = (\{R_o\} + \{Z\} - \{R\})^2 \rightarrow \text{Minimize } \Phi \tag{4}$$

namely,

$$\frac{\partial\Phi}{\partial\{\alpha\}} = \{0\} \tag{5}$$

Substituting $\{r\} = \{R_o\} - \{R\}$ into Eq. 4, and then solving Eq. 5 one can find {α} :

$$\{\alpha\} = -([F]^t\cdot[F])^{-1}\cdot[F]^t\cdot\{r\} \tag{6}$$

If a weighting matrix, [ρ] , is introduced to account for dimensional adjustment and field measurement uncertainty, then

$$\{\alpha\} = -([F]^t\cdot[\rho]\cdot[F])^{-1}\cdot[F]^t\cdot[\rho]\cdot\{r\}, \tag{7}$$

where, [ρ] is a diagonal matrix.

PRACTICAL APPLICATION

The SI method was applied to the Hokko Bridge (Fig. 1), which is a self-anchored, mono-cable and suspension bridge built in the northern part of the port of Osaka. The bridge has inclined hangers to increase the stiffness of the girder and to improve the dynamic behavior throughout the bridge. Pre-stress forces are introduced in the hangers so as to maintain tensile forces even when the maximum compressive forces are applied. Therefore, cable tension adjustment is an important procedure, just as it is for cable-stayed bridges.

Computer model

Not only backward analysis but also forward analysis is applied to the structural model (Fig. 2) of the erection steps by the finite deformation method.

Erection Method

After the stiffening girder blocks and towers are erected, the main cable was strung and the hangers were set in place (Fig. 3). The SI method was applied in step 2 of this example. The data for the SI method consisted of the sag lengths and elevation of the girder as field measurement items.

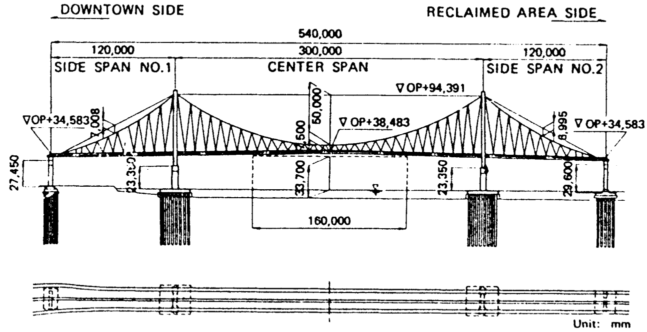


Fig. 1 General view of the Hokko Bridge

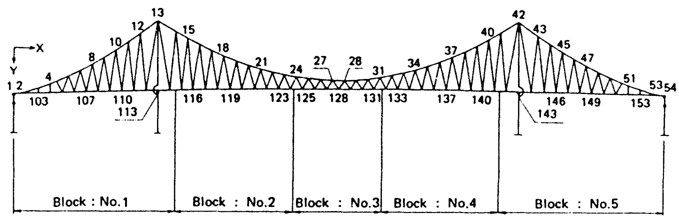


Fig. 2 Computer model of the Hokko Bridge

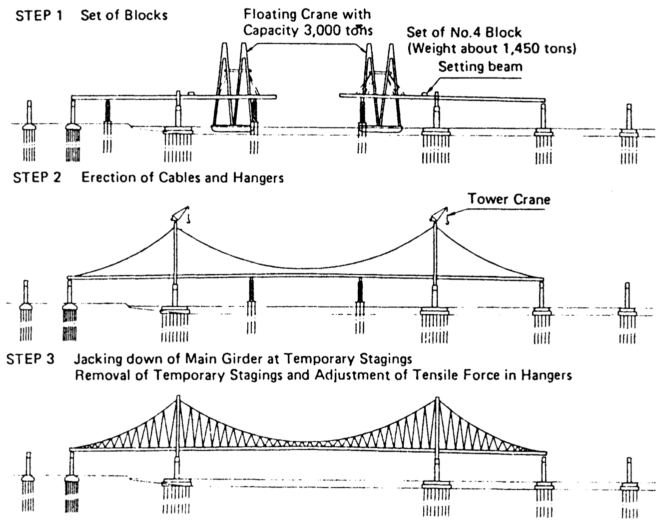


Fig. 3 Erection steps of the Hokko Bridge

Error factors

It is most important to select essential error factors in the application of the SI method. Engineers must select error factors intuitively in early erection steps, but repeated application of the SI method to each subsequent construction step helps them arrive at precise quantitative estimates of error factors. In this respect, cantilever erection is most suitable because of the many opportunities to apply the SI method in each cantilever step. However, large-block erection was used for the Hokko Bridge. Therefore, there were not many chances to apply the SI method. The example given here shows the results of the SI method.

Error factors are selected as listed in Table 1. Examples of error modes are shown in Fig. 4. These error modes do not correspond to Table 1, but are presented to demonstrate error mode shapes. Some examples of input values (= {R}) are shown in Table 2.

In large-block erection of girders, field welding was applied to join blocks of girders. This changes the nonstress girder camber by the thermal effect at the seam. To express this effect, a temperature difference between the upper deck and the bottom of the girder is assumed, as shown in Table 1.

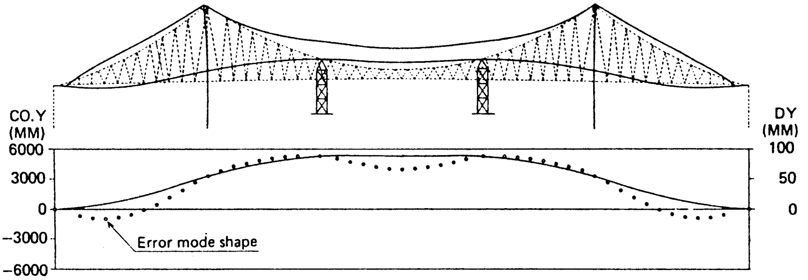
Table 1 Selected error factors

Error mode No.	Error factor	Contents
1	Dead load of girder	Girder weight 0.08 t/m increase in side span No.1
2	"	Girder weight 0.08 t/m increase in center span
3	"	Girder weight 0.08 t/m increase in side span No.2
4	Cable length in non-tensile force	Cable length 0.010 m decrease in side span No.1
5	"	Cable length 0.020 m decrease in center span
6	"	Cable length 0.010 m decrease in side span No.2
7	Girder section stiffness	Moment of inertia 3 % decrease in each side span
8	"	Moment of inertia 3 % decrease in center span
9	Non-stress girder camber	Temperature difference 3°C between an upper deck and a bottom of a girder in block No. 1
10	"	Temperature difference 3°C between an upper deck and a bottom of a girder in block No. 2
11	"	Temperature difference 3°C between an upper deck and a bottom of a girder in block No. 3
12	"	Temperature difference 3°C between an upper deck and a bottom of a girder in block No. 4
13	"	Temperature difference 3°C between an upper deck and a bottom of a girder in block No. 5
14	Cable Young's modulus	Young's modulus 3 % decrease in all cables
15	Girder position	Forced displacement of a girder-0.05 m in X-direction

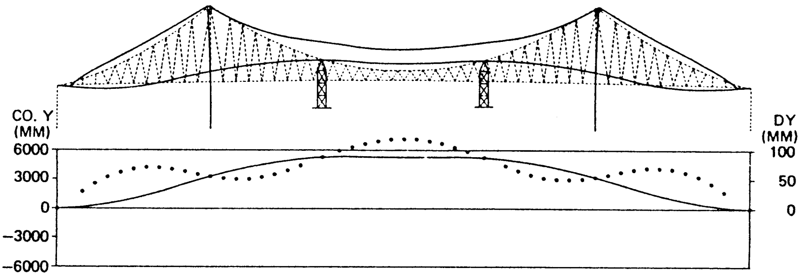
Table 2 Examples of input values Unit (m)

Nodal point No.	Calculated value with no error system(Y1)	Field measured value(Y2)	Y1-Y2
8	5.523 (Sag length)	5.486 (Sag length)	0.037
28	46.840 (Sag length)	46.758 (Sag length)	0.082
47	5.545 (Sag length)	5.666 (Sag length)	0.121
103	0.159	0.129	0.030
107	0.956	0.904	0.052
110	1.999	1.955	0.044
116	4.092	4.061	0.031
119	4.764	4.730	0.034
123	5.192	5.198	-0.006
128	5.155	5.160	-0.005
133	5.193	5.196	-0.003
137	4.761	4.743	0.018
140	4.084	4.079	0.005
146	1.995	1.959	0.036
149	0.961	0.918	0.043
153	0.146	0.121	0.025

Gase 1 --- Girder weight 5% increase in all spans



Gase 2 --- Temperature difference -2°C in all girders



Note) Co.Y --- Co-ordinate of Y
DY --- Displacement of Y co-ordinate by error mode shape. The abscissa expresses the scale length to the displacement.

Fig. 4 Examples of error model shape

Results

Calculated results for an error contribution rate vector are shown in Table 3. One can summarize the results as follows:

The girder weight of the side span No. 1 and the center span are heavier than the assumed values and that of the side span No. 2 is lighter than assumed. The cable length of the each side span is longer, but which of the center span is shorter than assumed. The moment of inertia for the bridge is smaller by more than 10%. From the results for error modes No. 9 to No. 13, the non-stress girder camber of the girder seems to be more significantly affected by field welding than originally estimated.

Young's modulus of cables is almost the same as the assumed value. The girder position was shifted by 22 mm due to installation error.

The above results are from a single application of the SI method. It is difficult to say whether these results are true or not, but the SI method gives many clues for better quality control in the construction. We achieved a structural computer model which was identical to the proto-type bridge by the SI method in this way (Fig. 5). Therefore, optimum shim plate thickness calculations [2] gave realistic values, which reduced the process of cable tension adjustment. Space limitations prohibit a detailed discussion of the process, but we were able to benefit from the good results of the SI method.

Table 3 Calculated results for an error contribution rate

Error mode No.	Error contribution rate :{α}	Assumed value	Calculated value
1	3.644	+0.080 t/m	+0.292 t/m
2	0.403	+0.080 t/m	+0.032 t/m
3	-2.548	+0.080 t/m	-0.204 t/m
4	-2.023	-0.010 m	+0.020 m
5	4.089	-0.020 m	-0.082 m
6	-2.002	-0.010 m	+0.020 m
7	4.478	-3 %	-13.4 %
8	5.001	-3 %	-15.0 %
9	-3.841	3°C	-11.5°C
10	6.341	3°C	+19.0°C
11	-2.105	3°C	-6.3°C
12	1.483	3°C	+4.4°C
13	-3.208	3°C	-9.6°C
14	-0.007	-3 %	+0.02 %
15	0.432	-0.050 m	-0.022 m

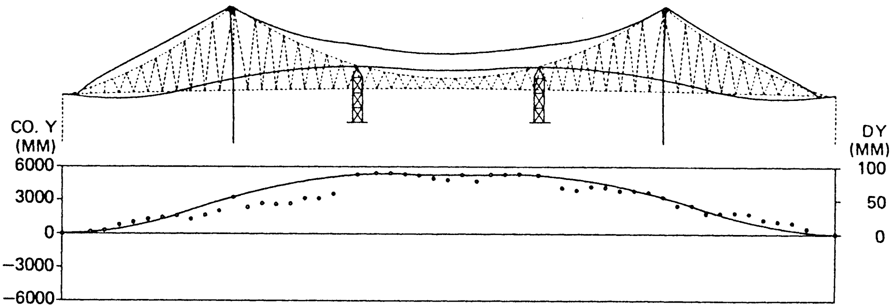


Fig. 5 Model fit to observed values

CONCLUSIONS

The application of a new method for estimating error factors quantitatively using the structural system identification technique is discussed.

A practical application of the SI method to the Hokko Bridge brought good results for the cable tension adjustment.

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