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Condition assessment of long span cable-stayed bridge

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Abstract: A condition assessment model for cable-stayed bridge was proposed, and a cable tension, elevation and frequency condition assessment model was then applied. With the optimized cable tensions as criterion, upper and lower bounds were then introduced. With the elevation of bridge completion as benchmark, and with the allowable vertical displacement of control points to interpolate to generate the upper and lower bounds of elevation, algorithm of condition assessment was programmed. Using moderate index model to interpolate linearly, and with the application of variable weight synthesizing principle (VWSP) and correlation of slope coefficient, according to a set of inspection and monitoring data, performance condition of cable tension, elevation and frequency were calculated. Results showed that with the decrease of balanced coefficient α, the assessment result is a process of degradation. The more divergent the variable weight is, the more severe is the degradation of the bridge component, and the larger is the curvature of curve α–V. Eventually, the model predicted that, for those bridge components whose grade of single survey point is exactly the same, the curvature of curve α–V is constant zero, i.e. there is no correlation between the assessment result and the balanced coefficient α. Numerical simulation showed that it agrees quite well with the expectation.

Key words: Cable-stayed bridge, Cable tension, Optimization, Analytic hierarchy process, Condition assessment, Correlation of slope coefficient, Balanced coefficient
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INTRODUCTION

The maintenance of bridge has become a major social concern because the number of damaged bridges has increased dramatically, thus the necessary development of a comprehensive bridge management system (BMS) (Kawamura and Miyamoto, 2003). Hence, condition assessment of concrete structure is a hotspot in the field of bridge engineering (Mazurek and DeWolf, 1990). Guo *et al*.(2002) presented an assessment system for reinforced concrete simply supported beam bridge structure with the introduction of analytic hierarchy process (AHP) and variable weight synthesizing principle (VWSP).

Definitely, the problem is to evaluate the performance condition of the bridge in service and to provide enough information for the administration in decision-making. When dealing with complicated problems such as the technical condition of a bridge, we should make the problems logicized and layering to establish a hierarchical model. Divide the major factors from the minor ones to avoid inconsistency, choose the indices that can basically affect the performance condition of the bridge structure.

The hierarchical model will finally give the current synthetical performance condition assessment of the bridge structure or its components according to monitoring and inspection data, structural analysis, damage identification and the apparent information from inspection and investigation. The assessment results will be taken as guidance in making decision, for instance, bridge maintenance or repairing. The task of condition assessment is primarily to assess the safety and durability of the bridge structure, including load carrying capacity, component stress, component deformation, cable

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tension, concrete crack, damage in covering layer, steel corrosion, etc.

Fig.1 shows a hierarchical assessment model of overall performance condition of a cable-stayed bridge (Catbas and Aktan, 2002; Guo *et al.*, 2002). In this model, the bridge structure is divided into six major components: substructure, girder, tower, cable, subordination and dynamic property (dy_property). Each component is also divided into some subcomponents and each subcomponent is characterized by its attributes called assessment indices.

The indexes in bottom layer of the assessment model can be classified into three categories according to the monitoring or inspection data type: (1) data describing the condition of components or simply classifying the condition level without numerical value, (2) data which are scalar quantities, (3) data which are vector quantities. Data of the first category should be quantified according to the standards. Lan and Shi (2001) proposed an approach to normalize these different types of monitoring data.

INDEX WEIGHT CALCULATION

Introduction of AHP method in calculation of index weight

It is an important problem to determine the weights of different indices of bridge condition assessment model, i.e., index's relative importance in multiple objective decision situations. There are many procedures for doing so. The analytic hierarchy process (AHP) developed by Saaty is popular in recent years because of its mathematical properties and simple implementation. In addition to Saaty's eigenvector method based on the pairwise judgement matrix, some researchers have proposed other procedures, such as the least square method (LSM) and the logarithmic least square method (LLSM), and so on. There are some advantages and disadvantages in those methods, respectively. LSM can easily determine the criteria importance coefficients by utilizing only the upper triangular elements of the pairwise judgement matrix in AHP.

In 2004, a questionnaire was sent to accredited universities and domain experts across China. Based on the methodologies in AHP, the questionnaire focused on the pairwise judgement matrix, i.e., assessment index's relative importance in multiple objective decision situations. The responses to a survey of condition assessment index weight are summarized below.

The judgement matrix is shown in Table 1. Of the 45 questionnaires sent, 12 were returned—5 from universities and 7 from administrations and institutions. In some cases the percentages in the tables do not add up to 100%, because in some instances certain items were left blank among the returned forms. Variance exists for weight calculation, due to unanswered responses. Accordingly, the forms containing blank were ignored. Table 2 and Table 3 show the raw data from one of the returned questionnaires.

Introduction of pairwise comparison methods

More than 20 years ago, Saaty proposed the analytic hierarchy process (AHP) method to decompose the multi criteria weighting of a set of elements into several steps of mono criterion weighting. Each step is then skipped with the use of a Pairwise Comparison (PC) method. Saaty also proposed the Eigenvector Pairwise Comparison method.

Table 1 The judgement matrix

	$\boldsymbol{B}_1$	$\boldsymbol{B}_2$	…	$\boldsymbol{B}_j$	…	$\boldsymbol{B}_n$
$\boldsymbol{B}_1$	b_{11}	b_{12}	…	b_{1j}	…	b_{1n}
$\boldsymbol{B}_2$	b_{21}	b_{22}	…	b_{2j}	…	b_{2n}
…	…	…	…	…	…	…
$\boldsymbol{B}_i$	b_{i1}	b_{i2}	…	b_{ij}	…	b_{in}
…	…	…	…	…	…	…
$\boldsymbol{B}_n$	b_{n1}	b_{n2}	…	b_{nj}	…	b_{nn}

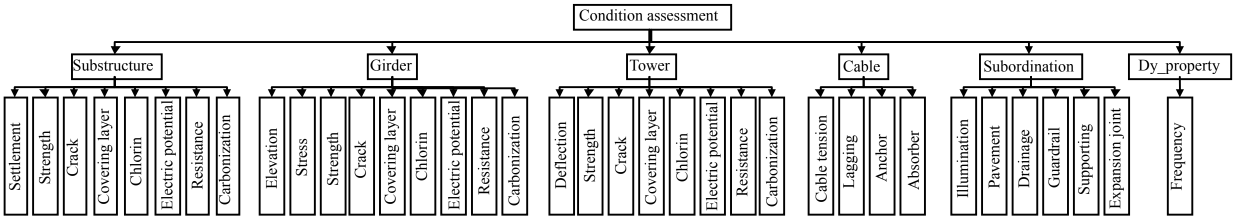


Fig.1 Condition assessment model of cable-stayed bridge

Table 2 The second layer of assessment hierarchy model

Index	Substructure	Girder	Tower	Cable	Subordination	Dy_property
Substructure	1	1	1	1	5	1/3
Girder	1	1	1	3	5	1
Tower	1	1	1	3	5	1/3
Cable	1	1/3	1/3	1	5	1/3
Subordination	1/5	1/5	1/5	1/5	1	1/3
Dy_property	3	1	3	3	3	1
Weight	0.226	0.184	0.186	0.239	0.034	0.130

Table 3 The third layer of assessment hierarchy model (girder)

Index	Elevation	Stress	Strength	Crack	Guard layer	Chlorin	Electric potential	Resistance	Carbonization
Elevation	1	3	3	3	5	5	7	7	7
Stress	1/3	1	1	1	3	3	5	5	5
Strength	1/3	1	1	1	3	3	5	5	5
Crack	1/3	1	1	1	3	3	5	5	3
Guard layer	1/5	1/3	1/3	1/3	1	1	3	3	1
Chlorin	1/5	1/3	1/3	1/3	1	1	3	3	1
Electric potential	1/7	1/5	1/5	1/5	1/3	1/3	1	1	1/3
Resistance	1/7	1/5	1/5	1/5	1/3	1/3	1	1	1/3
Carbonization	1/5	1/3	1/3	1/3	1/3	1	3	3	1
Weight	0.134	0.257	0.030	0.195	0.073	0.091	0.067	0.030	0.122

The method permits simplification of the distribution of 100% of importance into n elements (mono criterion case). The decision makers (DMs) may be one or more. The PC principle consists of comparing successively the relative importance of element i and element j, by means of assessment of their ratio. These comparisons are gathered in a square comparison matrix $\boldsymbol{A}$:

$$\boldsymbol{A}=\begin{bmatrix} b_{11} & b_{12} & \dots & b_{1j} & \dots & b_{1n} \\ b_{21} & b_{22} & \dots & b_{2j} & \dots & b_{2n} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ b_{i1} & b_{i2} & \dots & b_{ij} & \dots & b_{in} \\ \dots & \dots & \dots & \dots & \dots & \dots \\ b_{n1} & b_{n2} & \dots & b_{nj} & \dots & b_{nn} \end{bmatrix}.$$

A PC method starts from a matrix filled by the DMs to foresee a weight vector which will be the most representative of the composition of the comparisons. This weight vector is, in general, not unique and a variety of methods may coexist.

Despite this variety of methods and the resulting variety of results, these methods must converge to the same result when the matrix is consistent. A consistent matrix $\boldsymbol{A}$ complies with the cardinal transitivity expressed by $b_{ik}=b_{ij}b_{jk}$, $i,j,k=1,2,\dots,n$, $i\neq j$. In addition, $\boldsymbol{A}$ must be a reciprocal matrix, i.e., $b_{ij}=1/b_{ji}$, and $b_{ii}=1$, $i,j=1,2,\dots,n$, $i\neq j$.

If matrix $\boldsymbol{A}$ satisfies the cardinal consistency property, we have

$$\boldsymbol{AW}=\lambda\boldsymbol{W}, \tag{1}$$

where the weight vector $\boldsymbol{W}$ can be obtained by solving the above eigenvalue problem.

A pairwise comparison matrix $\boldsymbol{A}$ is made from decision maker's answers. Let n denote the number of elements of a certain layer. The component of the comparison matrix b_{ij}, $i,j=1,2,\dots,n$, represents the intensity of importance (as shown in Table 4) between items i and j. In AHP, the ratio scales for pairwise comparison range from 1 to 9 representing judgement entries where 1 is equally important and 9 is absolutely more important.

Consistency index of the pairwise comparison matrix

Since the components of the comparison matrix are obtained by comparisons between two items, its coherent consistency is not guaranteed as a whole. In

Table 4 Components b_{ij} of the comparison matrix

Intensity of importance	Description
1	*i* is as important as *j*
3	*i* is weakly more important than *j*
5	*i* is essentially more important than *j*
7	*i* is demonstratively more important than *j*
9	*i* is absolutely more important than *j*
2, 4, 6, 8	Intermediate values between adjacent values

AHP, consistency of the comparison matrix $\boldsymbol{A}$ with order n is usually measured by (Morera and Budescu, 2001)

$$C.R.=C.I./R.I., \tag{2}$$

$$C.I.=(\lambda_{\max}-n)/(n-1), \tag{3}$$

where $R.I.$ is average stochastic consistency index shown in Table 5, and $\lambda_{\max}$ is the maximum eigenvalue. The calculation of $\lambda_{\max}$ is as follows:

(1) Calculate the product of judgement matrix's indices of ith row,

$$M_i=\prod_{j=1}^{n} b_{ij}, \quad i=1,2,\ldots,n. \tag{4}$$

(2) Calculate nth root of M_i,

$$\bar{w}_i=\sqrt[n]{M_i}, \quad i=1,2,\ldots,n. \tag{5}$$

(3) Normalize the vector $\bar{\boldsymbol{W}}=(\bar{w}_1,\bar{w}_2,\ldots,\bar{w}_n)^{\mathrm{T}}$.

Let $w_i=\bar{w}_i/\sum_{j=1}^{n}\bar{w}_j$, and $\boldsymbol{W}=(w_1,w_2,\ldots,w_n)^{\mathrm{T}}$ is the eigenvector.

(4) Calculate the maximum eigenvalue $\lambda_{\max}$

$$\begin{aligned}\lambda_{\max}&=(b_{11}w_1+b_{12}w_2+\ldots+b_{1n}w_n)/nw_1\\&\quad+(b_{21}w_1+b_{22}w_2+\ldots+b_{2n}w_n)/nw_2\\&\quad+\ldots+(b_{n1}w_1+b_{n2}w_2+\ldots+b_{nn}w_n)/nw_n.\end{aligned} \tag{6}$$

It should be noted that $C.R.\geq 0$ holds. The smaller the value of $C.R.$ is, the higher the degree of consistency. Comparison matrix is consistent when $C.R.<0.1$, otherwise, the comparison matrix should be updated.

Table 5 Average stochastic consistency index *R.I.*

Order	*R.I.*	Order	*R.I.*
1	0	6	1.26
2	0	7	1.36
3	0.52	8	1.41
4	0.89	9	1.46
5	1.12	10	1.49

Index weight

With the above-mentioned method, according to the data acquired from the returned questionnaire, indices weight of the assessment model were obtained. Part of the indices weight are shown in Table 2 and Table 3.

PRINCIPLE OF CONDITION ASSESSMENT

Variable weight synthesizing principle (VWSP)

Variable weight synthesizing principle (VWSP) considers the balance between indices in assessment, while normal weight synthesizing principle (NWSP) does not take it into account. Generally, VWSP is the evolution of NWSP.

Mode of NWSP:

$$V_0=\sum_{j=1}^{m} w_j^{(0)} x_j. \tag{7}$$

Mode of VWSP:

$$V=\sum_{j=1}^{m} w_j\left(x_1,\ldots,x_m,w_1^{(0)},\ldots,w_m^{(0)}\right)x_j, \tag{8}$$

where V_0 and V represent overall assessment result of normal weight synthesizing and variable weight synthesizing respectively, x is the performance condition vector of assessment indices, $w_j^{(0)}$ is the normal weight or initial weight of the jth assessment index, while w_j is the variable weight through balanced function (Liu, 1997).

Assume $B(x_i,\ldots,x_m)$ is the balanced function, and then

$$w_j\left(x_1,\ldots,x_m,w_1^{(0)},\ldots,w_m^{(0)}\right)=w_j^{(0)}\frac{\partial B}{\partial x_j}\Bigg/\sum_{k=1}^{m}\left(w_k^{(0)}\frac{\partial B}{\partial x_k}\right) \tag{9}$$

is the corresponding variable weight mode of the balanced function which can be defined as:

$$B(x_1,...,x_m)=\sum_{j=1}^{m}x^{\alpha},\quad 0<\alpha\le 1. \tag{10}$$

Specially, the variable weight mode should be normalized, continuous and penitentiary, which means the variable weight is monotonically decreasing on the parameter x.

The application of VWSP in assessment has solved the problem that some indices with bad health condition contribute little to the overall condition assessment but will absolutely affect the overall performance condition of the bridge structure. Variable weight based on VWSP is actually an update of normal weight. VWSP magnifies the weight of those indices with bad health condition. Hence, it can explicitly exhibit the effect of the indices with bad condition on the overall performance condition of the bridge.

Theory of grey correlation

Now, we write the reference sequence $\boldsymbol{X}_0$ and test sequence $\boldsymbol{X}_i$ in the form $\boldsymbol{X}_0=[x_0(1),x_0(2),\dots,x_0(n)]$, and $\boldsymbol{X}_i=[x_i(1),x_i(2),\dots,x_i(n)]$; the correlation of slope coefficient r is expressed in (Deng, 1982):

$$r(\boldsymbol{X}_0,\boldsymbol{X}_i)=\frac{1}{n-1}\sum_{k=1}^{n-1}\left[1+\left|\frac{a^{(1)}(x_0(k+1))}{x_0(k+1)}-\frac{a^{(1)}(x_i(k+1))}{x_i(k+1)}\right|\right]^{-1}, \tag{11}$$

where, $a^{(1)}(x_0(k+1))=x_0(k+1)-x_0(k)$ and $a^{(1)}(x_i(k+1))=x_i(k+1)-x_i(k)$, $k=1,2,\dots,n-1$.

ANALYSIS OF BRIDGE CONDITION ASSESSMENT

Bridge condition assessment evaluates the performance of bridge structures based on inspected and monitoring data.

Wenhui Bridge shown in Fig.2 was completed in 2003. As known to all, dead loads and live loads, unanticipated weather condition, ageing and so on will gradually harm it. This will not only affect the safe running, but reduce the serviceability of the bridge structure. Hence, it is of great significance to analyze the performance condition of the bridge. The major subject of this paper is to summarize a comprehensive assessment system based on practical monitoring and inspection.

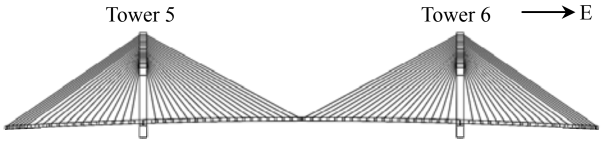


Fig.2 Finite element division (Elevation of Wenhui Bridge)

Assessment of cable tension

Assessment of cable tensions evaluates the health condition of cables based on inspected cable tensions. Firstly, criteria for evaluation should be determined. A feasible way is to focus on the design cable tensions. However, for long-span prestressed concrete bridge that has been in service many years, the stress level of the structure has changed much due to shrinkage and creep of concrete and complicated spatial effect. Therefore, design cable tensions cannot be the current optimum tensions. For the sake of the criteria for evaluation, cable tension optimization of Wenhui Bridge has been implemented. In this optimization, shrinkage and creep effects of concrete were considered. The optimization result was taken as the criteria for evaluation.

1. Cable tension optimization model

Assume a reasonable moment distribution $\boldsymbol{S}_{\text{c}}$, compared to moment distribution $\boldsymbol{S}_0$ which is under design cable tensions $\boldsymbol{T}_0$, the deviation is:

$$\Delta\boldsymbol{R}=\boldsymbol{S}_{\text{c}}-\boldsymbol{S}_0. \tag{12}$$

If there is an adjustment of cable tension vector $\Delta\boldsymbol{T}$, which agrees with

$$\boldsymbol{C}\Delta\boldsymbol{T}=\Delta\boldsymbol{R}, \tag{13}$$

hence, the cable tensions under dead load expressed as

$$\boldsymbol{T}=\boldsymbol{T}_0+\Delta\boldsymbol{T} \tag{14}$$

will make the moment distribution consistent with the objective.

In Eq.(13), $\boldsymbol{C}$ is tension-bending moment influence matrix (Xiao and Xiang, 1998), as shown in Fig.3, $\boldsymbol{T}_0$ is the design cable tension vector and $\boldsymbol{T}$ is the optimized cable tension vector in Eq.(14).

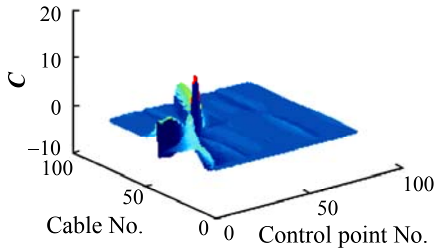


Fig.3 Influence matrix of cable tension-bending moment of girder

In optimization, cable tension should satisfy certain requirements. Firstly, the tensile stress of cables should be greater than zero and less than 40% of the design strength, which is stated as:

$$0<T_i<0.4R_iA_i, \qquad i=1,2,\ldots,m, \tag{15}$$

where T_i and A_i represent the cable tension and cross section area of the ith cable respectively, and R_i represents the design strength of the ith cable.

Secondly, constraining the non-homogeneous coefficient of the adjacent cables. Hence, cable tensions distribution will be in uniform.

$$Z_i=(T_{i-1}+T_{i+1})/2-T_i, \qquad i=1,2,\ldots,m-1, \tag{16}$$

where T_{i-1}, T_i and T_{i+1} are the continuous adjacent 3 cable tensions, and Z_i is the non-homogeneous cable tension.

Thirdly, after the optimization, elevation of girder should be in a smooth curve, whose constrained equation is expressed as:

$$\boldsymbol{D}\Delta\boldsymbol{T}=\boldsymbol{\delta}, \tag{17}$$

$$|\delta_i|\le\varDelta_i, \qquad i=1,2,\ldots,l, \tag{18}$$

where $\boldsymbol{D}$ represents $l\times m$ cable tension-elevation influence matrix. $\boldsymbol{\delta}$ is the increment of vertical displacement corresponding to the adjustment of cable tensions. $\boldsymbol{\varDelta}$ is the allowable vertical displacement of control points. After consulting corresponding design code of bridge, reasonable magnitude of $\boldsymbol{\varDelta}$ was determined.

The optimization problems can be classified into constrained and unconstrained form depending on whether or not constraints are imposed. In constrained optimization, which is the case in many practical problems, the design variables cannot be chosen arbitrarily, they must satisfy certain explicit requirements. Optimization algorithms seek an approximate solution by proceeding iteratively. They begin with an initial guess of the optimal values of the variables and generate a sequence of improved estimates until they reach the solution. Hence, the name hill-climbing or downhill methods are popular, since the iterations go gradually uphill or downhill on the surface of the objective function. The strategy used to move from one iteration to the next distinguishes one algorithm from another.

Optimization is used to find a set of design parameters which can be defined as optimal. Here, the objective function $f(\Delta\boldsymbol{T})$, to be minimized are subjected to constraints in the form of inequality constraints, and lower and upper parameter bounds α_j and β_j. The constrained optimization problem is stated as (Wang *et al.*, 1991)

$$\begin{aligned}&\varOmega=\min f(\Delta\boldsymbol{T})=\left\|(\boldsymbol{C}\Delta\boldsymbol{T}-\Delta\boldsymbol{R})\right\|^2,\\ &\text{s.t.}\quad 0<T_i<0.4R_iA_i, \qquad i=1,2,\ldots,m;\\ &\qquad\ \alpha_j<Z_j<\beta_j, \qquad j=2,\ldots,m-1;\\ &\qquad\ |\delta_k|\le\varDelta_k, \qquad k=1,2,\ldots,l,\end{aligned} \tag{19}$$

where $\Delta\boldsymbol{T}$ is the vector of design parameters, α_j and β_j represents the lower and upper bounds of non-homogeneous cable tensions respectively, and the reasonable magnitude was determined by dibble-dabble.

The key problem of the cable tension optimization in this paper is, theoretically, to search the objective moment distribution $\boldsymbol{S}_\mathrm{c}$. The dead load moment distribution, which made the absolute value of negative moment envelope diagram equal to those of positive one under combined loads, was taken as the objective moment distribution.

Wenhui Bridge was analyzed in a plane model shown in Fig.2. It was divided into 286 elements, including 162 beam elements, 48 tower elements and 76 cable elements.

By considering 1/2 effect of live load with the similar conception of ‘anti-arch degree’, the objective moment distribution $\boldsymbol{S}_\mathrm{c}$ is easy to obtain as expressed in (Wu *et al.*, 2005)

$$\boldsymbol{S}_\mathrm{c}=-(\boldsymbol{M}_\mathrm{h\_max}+\boldsymbol{M}_\mathrm{h\_min})/4, \tag{20}$$

where $\boldsymbol{M}_{\mathrm{h\_max}}$ and $\boldsymbol{M}_{\mathrm{h\_min}}$ represents maximum and minimum of the live loads moment effect under combined load, respectively.

By trial method, appropriate lower and upper bounds of non-homogeneous cable tensions were determined: $\alpha_j=-50$ kN, $\beta_j=50$ kN, $i=2,\ldots,m-1$. In elevation constraint, three control points including centre of midspan and of two side spans were selected. Allowable vertical displacement of the control points was $\Delta=[5,2,2]^{\mathrm{T}}$ cm, and the corresponding optimized cable tensions under dead load was shown in Fig.4.

Calculation showed that compared to the result of unconstrained optimization, constrained optimization can successfully avoid nonuniformity of cable tensions, and that the distribution of cable tensions is relaxative.

2. Cable tensions assessment model and calculation

With the application of variable weight synthesizing principle (VWSP) and theory of grey correlation, based on analytic hierarchy process (AHP) method (Lan and Shi, 2001), performance condition of cables of Wenhui Bridge was assessed. The assessment model of cable tension is shown in Fig.5.

Data on cable tension belong to the third category. Moderate index model (Zhu, 1996) was adopted to assess single survey point of cable tension.

There are 76 cables on the south and north side of Wenhui Bridge, respectively. Initial weight of the survey points was set to be equal, and the optimized cable tensions, $\boldsymbol{X}_0$, was taken as the criteria for evaluation, as shown in Fig.4. Fig.6 shows the current inspected cable tensions, $\boldsymbol{X}_i$. Based on the criteria, single survey point assessment result is 100 when there is no variation of the cable tension and 0 when there is a variation of 40% and linear interpolate was used to generate the intermediate variation.

With the application of correlation of slope coefficient, based on Matlab, cableT was programmed. The performance condition of cables was assessed, with assessment results shown in Fig.7 and Table 6.

Elevation assessment model and calculation

Similarly, with the application of VWSP and theory of grey correlation, based on AHP method, elevation condition of girder was assessed. The assessment model of elevation is shown in Fig.8.

Elevation condition assessment evaluates the health condition of line shape girder based on inspected elevation data. Here, the elevation of completed bridge was chosen as the criteria for evaluation.

Regarding the safe running of prestressed concrete bridges, the vertical displacement increment should be less than 1/500 of calculated span under regular service critical condition.

Here, seven interpolation control points were chosen. They are the ends of the bridge, centre of the midspan and of two side spans, and the spots where girder intersects Tower 5 and Tower 6.

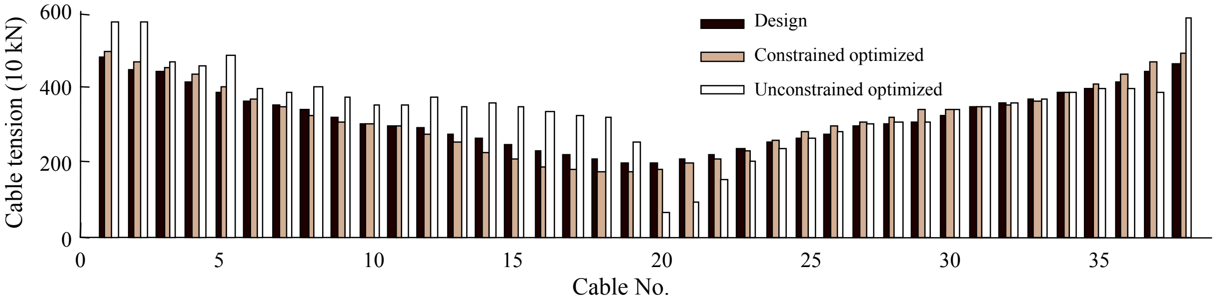


Fig.4 Constrained and unconstrained optimized cable tensions under dead loads and design cable tensions

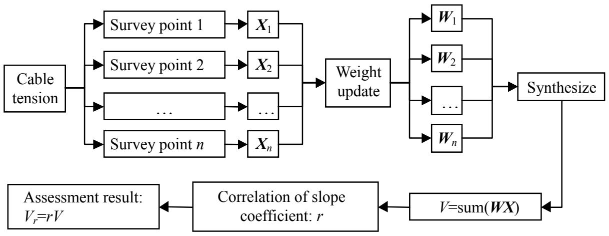


Fig.5 Assessment model of cable tensions

Fig.9b shows lower and upper bounds of 23 survey points on the girder, with the bounds obtained by cubic interpolation on 7 control points.

There are 23 survey points on both the south and north side of Wenhui Bridge, respectively. Initial weight of the survey points was set to be equal, and the elevation of completed bridge, $\boldsymbol{X}_0$, was taken as

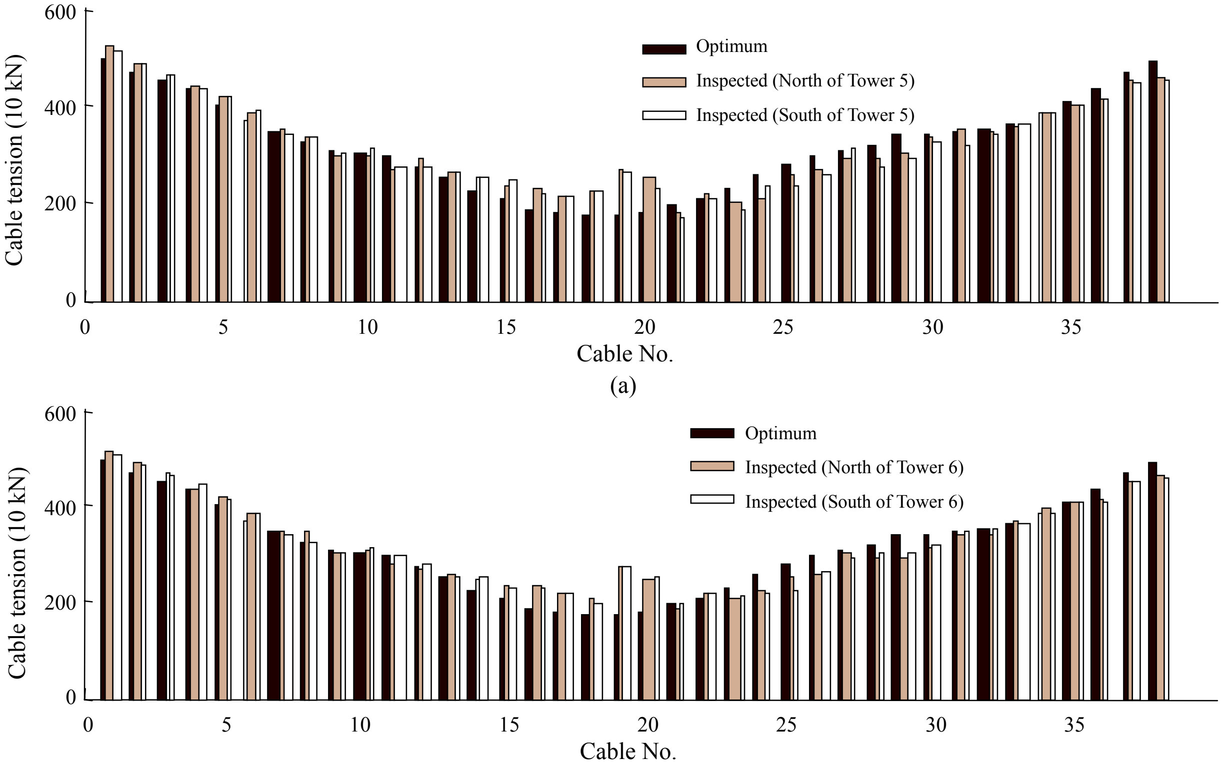


Fig.6 Optimum cable tensions and inspected cable tensions (axes *x* denote cable No., from interior to exterior of the towers). (a) Cable tensions of Tower 5; (b) Cable tensions of Tower 6

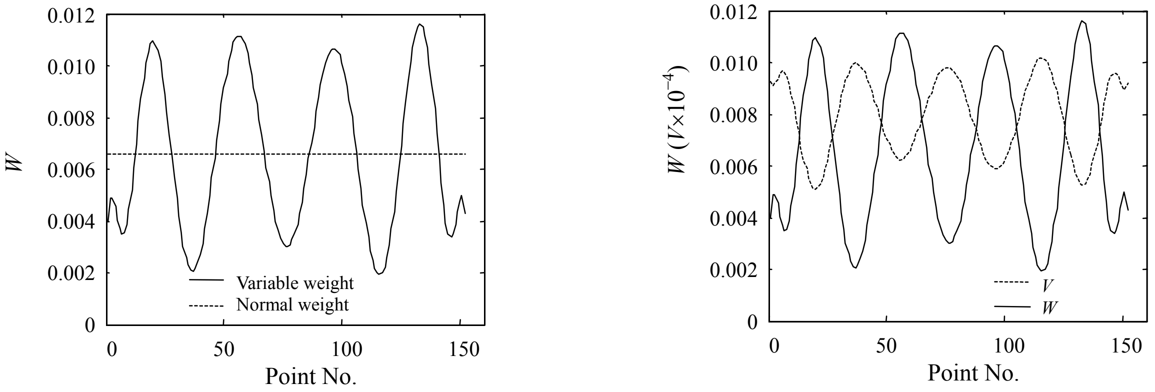


Fig.7 Condition assessment of cables. (a) Weight of single survey point; (b) Grade and weight of single survey point

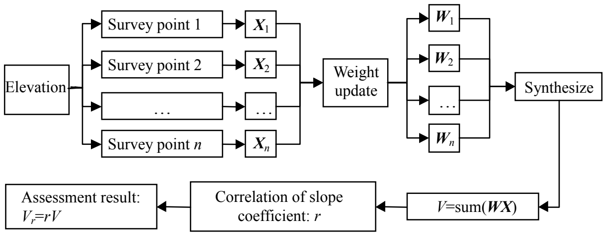
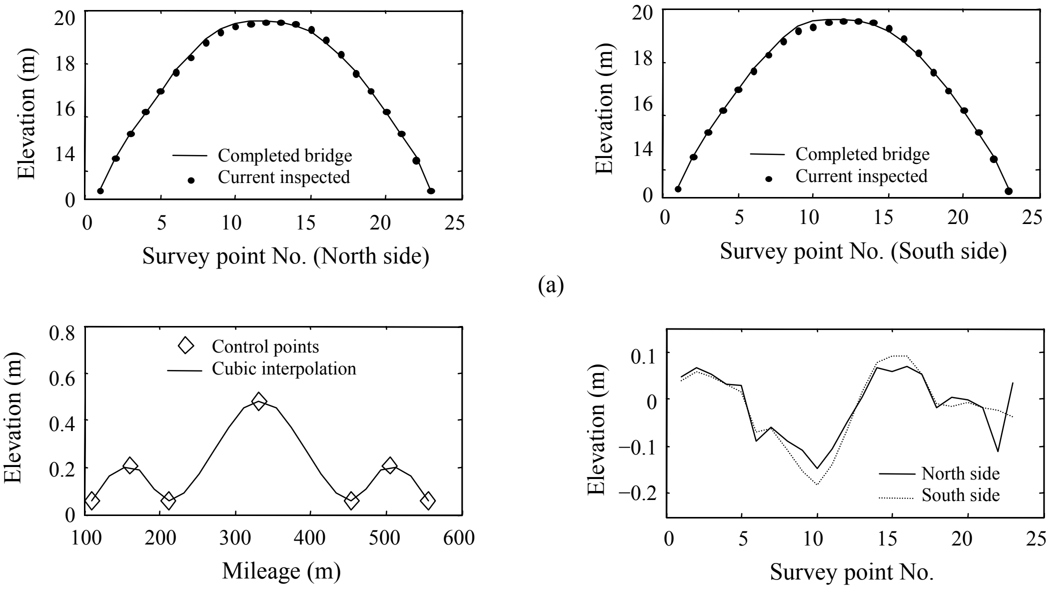


Fig.8 Assessment model of elevation

Table 6 Result of synthetic assessment condition that changes with the balanced coefficient α

Item	r	G^c	G^v			
		α=1	α=0.5	α=0.2	α=0.1	α=0
Cable tension	0.94	74.70	67.80	61.30	58.70	55.90
Elevation	1.00	77.00	73.70	71.00	69.90	68.80
Frequency	−	89.67	89.67	89.66	89.65	89.64

r denotes correlation of slope coefficient; α denotes balanced coefficient, G^c, G^v denotes assessment results of normal weight synthesizing and variable weight synthesizing, respectively



(b) (c)

Fig.9 Schematic plan of girder elevation. (a) Elevation of completed bridge and current inspected elevation; (b) Elevation of interpolation; (c) Variation of elevation

the criteria for evaluation, which is shown in Fig.9a which also shows the current inspected elevation $\boldsymbol{X}_i$. Based on the criteria, single survey point assessment result was 100 when there was no elevation increment and 0 when increment reached lower and upper bounds, and linear interpolate was used to generate the intermediate increment assessment result. Fig.9c shows the elevation increment in the south and north side of Wenhui Bridge respectively.

Elevation data belonged to the third category. Moderate index model (Zhu, 1996) was adopted to assess single survey point of elevation. Based on the current inspected elevation data, health condition of girder elevation was assessed.

With the application of correlation of slope coefficient, based on Matlab, *Elevation* was programmed. Health condition of girder elevation was assessed after current inspected elevation data was input into the programme. The assessment results are shown in Fig.10 and Table 6.

Dynamic property assessment and experiment

Dynamic properties, especially the theoretical inherent frequencies of the bridge structure were obtained from finite element analysis (FEA) for which the model (shown in Fig.11) was set up and run using ANSYS.

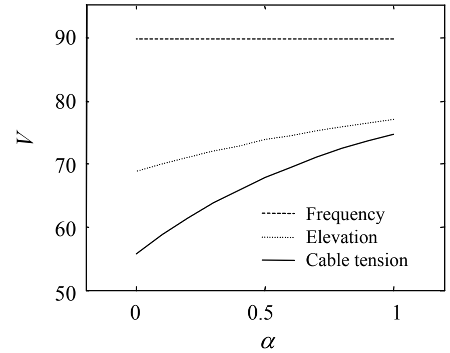


Fig.10 Sensitivity of variable weight synthesis grade to balanced coefficient

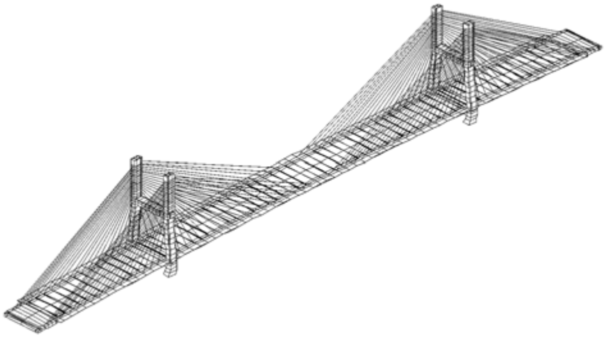


Fig.11 3D FEA model of Wenhui Bridge

According to the dynamic characteristic of Wenhui Bridge, the mid-span and the east side-span were selected for the dynamic experiment. Acceleration sensors and dynamic instrument were fixed on the bridge for data acquisition.

The total number of dynamical survey points on the bridge is 32, and 16 on each side. Each survey point included 2 vertical and transverse acceleration sensors.

Primary experiment includes: (1) eigenfrequency during environment vibration; (2) dynamic frequency response when experiment vehicles move on the bridge at a certain velocity; (3) dynamic frequency response when vehicles jump and brake on the bridge. Results of dynamic analysis are summarized in Table 6.

According to the theoretical and experimental frequency, and referring to the structure technical grade criterion, dynamic property of Wenhui Bridge was evaluated. The grade criterion is shown in Fig.12.

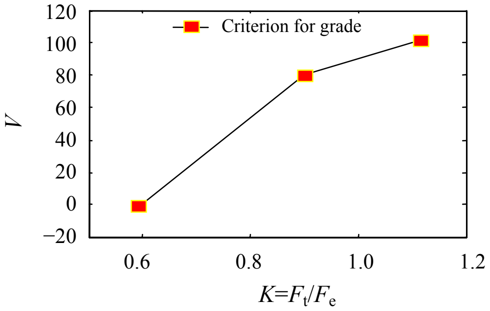


Fig.12 Criterion for grade (*K*-*V*)

Frequency data belong to the second category. Positive index model (Zhu, 1996) was adopted to assess single survey point. Experimental frequency data were used to assess the dynamic property condition.

Initial weight of the survey point was set to be equal. Matlab and the criteria for grade were used to program Frequency. The assessment results are also shown in Fig.10 and Table 6.

Relationship between assessment result and balanced coefficient α

Calculation showed that with the decrease of balanced coefficient α, the assessment result was a process of degradation; the more divergent the variable weight was, the more severe the degradation of the bridge component, and the larger the curvature of curve α–V (Fig.10).

Fig.10 clearly shows that the degeneration speed rate was largest for the assessment of cable tension, and next elevation, then frequency.

The condition assessment curves of the items, i.e., frequency, elevation, and cable tension are given in Fig.13 clearly showing that the condition assessment curve is relaxative and smooth for frequency, although drastically vibrating for elevation and cable tension. Variable weight synthesizing principle (VWSP) is sensitive for items whose condition assessment curve vibrates drastically, but obtuse for those whose condition assessment curve is smooth and relaxative (Fig.14). It well explains why the degeneration speed rate is largest for the assessment of cable tension, and next elevation, then frequency.

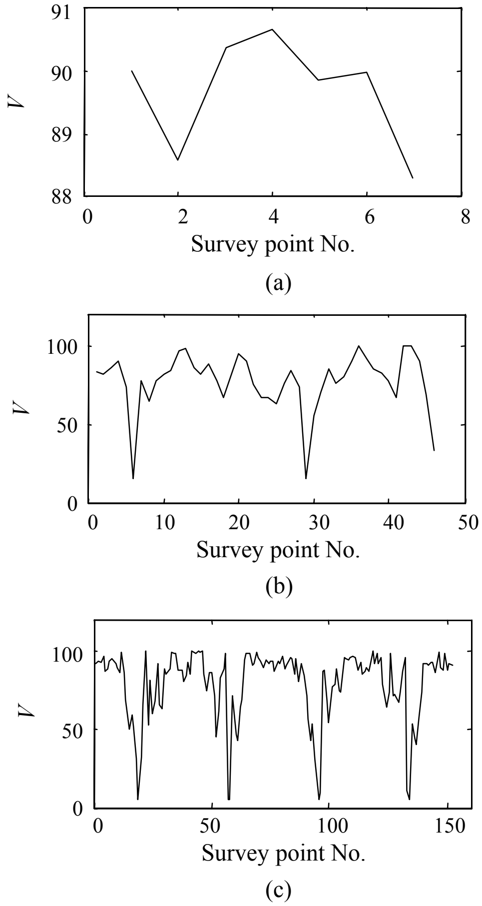


Fig.13 Assessment result curve of survey points. (a) Frequency; (b) Elevation; (c) Cable tension

Eventually, VWSP predicted that, for bridge component with grade of single survey point being exactly the same, the curvature of curve α–V is a con-

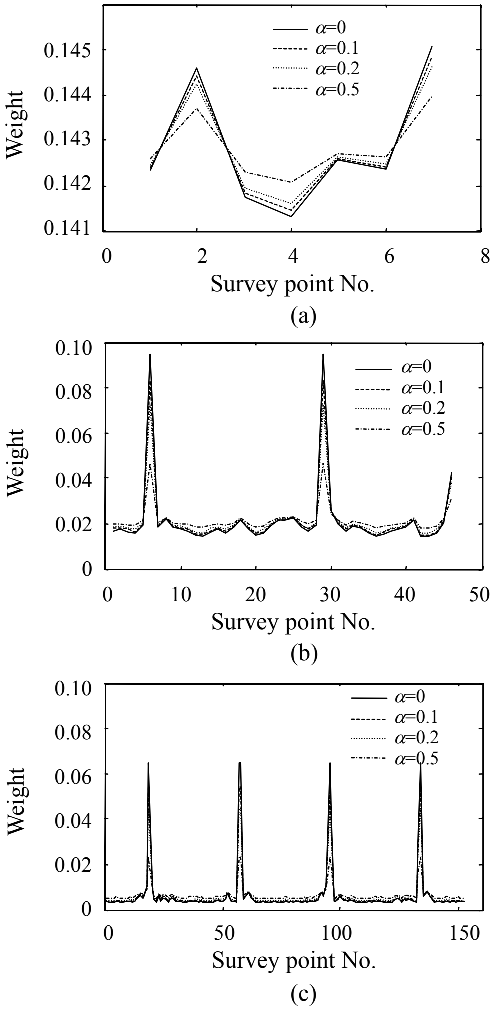


Fig.14 Variable weight of survey points. (a) Frequency; (b) Elevation; (c) Cable tension

stant zero, i.e., there is no correlation between the assessment result and the balanced coefficient α. On condition that the grade of every single survey point is 75, numerical simulation showed that it agrees quite well with the expectation, as shown in Fig.15.

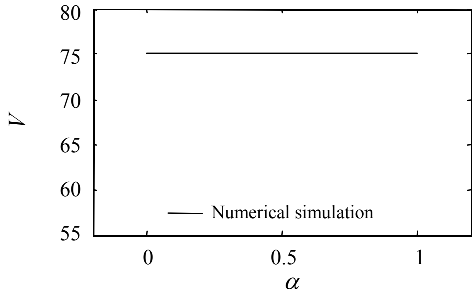


Fig.15 Numerical simulation of α−V

Overall performance condition assessment of Wenhui Bridge

With the inspected cable tensions, elevation, and frequency data, the overall performance condition of Wenhui Bridge was eventually evaluated as shown in Fig.16. From the calculating result, we can see that with the decrease of balanced coefficient α, the assessment result is a process of speeded-up degradation.

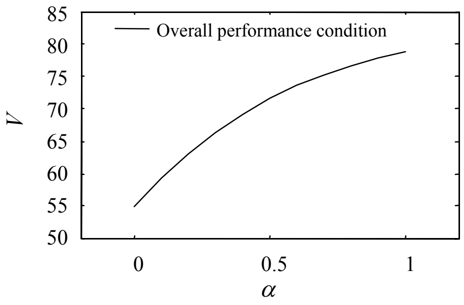


Fig.16 Overall performance condition assessment with the variation of balanced coefficient α

CONCLUSION

(1) A constrained optimization method for cable stayed bridge was applied with the moment distribution of girder under dead loads as optimization objective variables, and the increment of cable tension as optimization variables. Then the reasonable moment distribution of girder under dead loads was obtained with conception similar to that of 'anti-arch degree'. By constraining the coefficient of asymmetry of the cable tensions, reasonable cable tensions under dead loads were obtained.

(2) The application of VWSP in condition assessment has solved the problem that some indices with bad health condition contribute little to the overall condition assessment but will adversely affect the overall performance condition of the bridge structure. Variable weight based on VWSP is actually an update of normal weight. VWSP has successfully magnified the weight of those indices whose health condition is relatively bad. Hence, it can explicitly exhibit the effect of the indices with bad condition on the overall condition of the bridge structure.

(3) With the decrease of balanced coefficient α,

the assessment result is a process of degradation. The more divergent the variable weight is, the more severe is the degradation of the bridge component, and the larger is the curvature of curve α–V.

(4) The VWSP model predicted that, for those bridge component whose single survey point grade is exactly the same, the curvature of curve α–V is a constant zero, i.e. there is no correlation between the assessment result and the balanced coefficient α. Numerical simulation showed that it agrees quite well with the expectation.

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