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Computer-Aided Cable Adjustment of Stayed Bridges

Réglage des câbles de ponts haubannés à l'aide de l'ordinateur

Computer-Unterstützte Justierung der Kabel von Schrägseilbrücken

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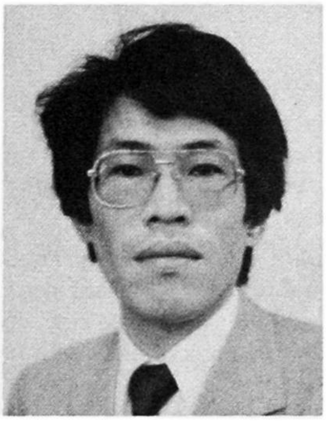

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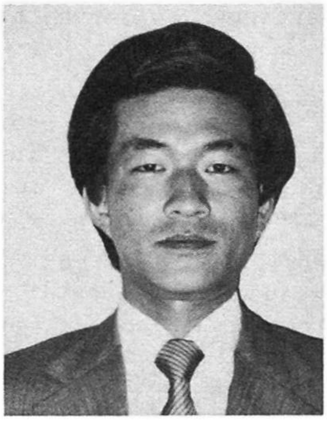

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SUMMARY

The cable length adjustment is one of the most important steps in the erection of cable stayed bridges. The paper presents an effective computer-aided method. The big advantages of utilizing the computer on the site are also discussed.

RÉSUMÉ

Le réglage de la longueur des câbles est un des points les plus importants dans le montage de ponts haubannés. L'article présente une méthode efficace de réglage, à l'aide d'un mini-ordinateur et présente les avantages de l'utilisation de l'ordinateur sur le chantier.

ZUSAMMENFASSUNG

Die Justierung der Kabellängen ist eine der wichtigsten Aufgaben beim Bau von Schrägseilbrücken. Der Beitrag bringt hierfür eine leistungsfähige Methode, die durch einen Mini-Computer unterstützt wird. Es wird angezeigt, dass der Einsatz eines Computers auf der Baustelle selbst Vorteile bringt.

1. INTRODUCTION

Cable adjustment is one of the most important steps in the erection of cable-stayed bridges. Since cable-stayed bridges are highly statically indeterminate structures, cable tensions are sensitive to cable length errors and it can hardly be expected that tension errors remain less than the tolerance limits if no adjustment is made.

The cable adjustment is necessary not only to avoid the damage of cables and related structures from overstressing but to make the cable stiffness, which is a function of the tension as is well known, equal to the required value. Thus, the objective of the cable adjustment was to reduce tension errors originally, though it has been revealed that this is not always valid. In fact, some papers [1,2] report that the adjustment which aims to minimize tension errors often causes the unacceptable distortion in bridge structures.

The object of this paper is to present the way in which the cable length adjustment can be done more reasonably and effectively. The mini-computer system which was developed to serve this purpose is also described.

2. OBJECTIVE OF CABLE ADJUSTMENT

Since the cable adjustment is made in a manner to change the cable length using adequate provisions, shim-plates, screws, etc., it is apparent that the proper cable length adjustment cancels the effect of cable length errors completely.

Actually, cable tensions are forced to deviate from the theoretically required values not only because of the cable length error but because of the effects of numerous factors. Since the correct assortment of these deviations according to their causes is almost impossible, the tension difference between observed and required, which is the substantial object of the adjustment, unavoidably include the deviations which are not caused by the cable length error. Furthermore, there is no reason to reject the deviations which are not due to the cable length error even if the identification is possible, because there is a fair possibility of improvement by means of cable adjustment.

The primary purpose of the cable adjustment is to reduce the error in cable tensions as previously mentioned, but this cannot be justified in the actual situation. Since bridge structures respond variously according to the characteristics of each cause, the adjustment paying attention only to the tension error is not always successful. It appears that, in most cases, the adjustment to minimize the tension error results in the excessive distorsion of bridge decks and pylons: This naturally may cause the overstress in the structures though the tension error has been eliminated. As for highway bridges, the deck should be prevented from irregular profile from the standpoint of proper road alignment as well.

Thus, it is concluded that the cable adjustment should be conducted in a manner to reduce the overall error of the whole structure whatever the causes may be.

Herein, it is noteworthy to point out that the raw deviations which are obtained from the measurement performed on the erection site possibly include those which should not be corrected by the cable adjustment. A typical example is the response to fluctuating thermal loads. Usually, in order to reduce the effect, the cable adjustment is made when the whole bridge structure is at a relatively uniform temperature. For the more accurate adjustment, it is recommended to subtract the thermal effect from the raw deviation by measuring the temperature distribution within the structure.

3. OPTIMUM CABLE ADJUSTMENT

3.1 Influence Matrix and Cable Adjustment

If displacements are so small that the nonlinearity is negligible, the response to the change in cable length is expressed in matrix form:

$$R = A \cdot DL \qquad \text{.........................(1)}$$

where R and DL are column vectors which represent the response and the change in cable length, respectively. A is the matrix which works as a linear operator between R and DL. The components of the column vector R are to be chosen properly so that they represent the principal behavior of the whole structure. Usually the cable tensions, the bridge deck geometry measured at appropriate points, and the horizontal displacement of the pylon top appear to be necessary. The stress of the girder and/or pylon, the resultant force at bearings, etc. may be added if required.

The matrix A is called an influence matrix since it expresses the influence of the change in cable length on the responses. To obtain A, standard computer programs can be utilized. If stays are arranged in two planes, the bridge has to be modeled as a three-dimensional space frame.

As the adjustment is conducted to cancel the observed deviation, the result is expressed by

$$E = D - R \qquad \text{.........................(2)}$$

where D is the deviation to be corrected by the adjustment and E is residual. Here, thermal effects are assumed to have been removed from D by adequate means. Substituting Eq.(1) into Eq.(2) gives

$$E = D - A \cdot DL \qquad \text{.........................(3)}$$

From the standpoint of reducing the residual, it is reasonable to consider that the ideal adjustment will be given by E = 0.

$$A \cdot DL = D \qquad \text{.........................(4)}$$

If the matrix A is square and not singular, premultiply by the inverse of A, the adjustment DL is given by

$$DL = A^{-1} \cdot D \qquad \text{.........................(5)}$$

This expression may be utilized, if the number of the response items in vector D is equal to the number of cables to be adjusted. The adjustment which aims at the reduction of cable tension error solely is a typical example.

3.2 Optimum adjustment

The newly developed method for the cable adjustment is based upon the concept that the overall error has to be reduced uniformly. This causes the increment of the number of items in D and results in A of rectangular matrix. In this case, A does not have the inverse and the expression similar to Eq.(5) is not available any more.

In order to solve the problem, the minimum residual is substituted for E=0 as the target for cable adjustments. The sum of the squares of the components in E is:

$$S = \sum_{i=1}^{n} e_i^2 = \sum_{i=1}^{n} (d_i - \sum_{j=1}^{m} a_{i,j} \cdot dl_j)^2 \qquad \text{...................(6)}$$

in which e_i, d_i, and dl_j are the components of vector E, D and DL respectively, and $a_{i,j}$ is the component of matrix A. The values of dl_j which will make S as small as possible are obtained to equate to zero the first partial derivatives with respect to dl_j. The solution, the optimum adjustment, is expressed in matrix form:

$$DL = ({}^{t}A \cdot A)^{-1} \cdot {}^{t}A \cdot D \qquad \text{.............................(7)}$$

where ${}^{t}A$ is the transpose of A.

In the application of Eq.(7), attention must be paid to the fact that the weight of each error component in the quantity S depends on the expression of units. The appropriate transformation of all variables into dimensionless form is recommended to reduce all residuals evenly. Conversely, if biased weights are employed, a stress is laid on the reduction of the residual of heavily weighted items. Since there is a possibility of using biased weights from the engineering point of view, the following expression may be more convenient for practical use.

$$DL = ({}^{t}A \cdot W \cdot A)^{-1} \cdot {}^{t}A \cdot W \cdot D \qquad \text{.....................(8)}$$

where W is the diagonal matrix, in which the main diagonal elements are the weight coefficients. Once the adjustment is obtained, the residual, the result of the adjustment, can be predicted by sustituting DL into Eq.(3).

The validity of the proposed optimum adjustment, Eq.(8), is investigated by numerical simulations [3], though the detailed explanation is not given because of the space limitation.

4. MINI-COMPUTER SYSTEM

4.1 General Consideration

For the application of the method presented in the foregoing chapter, introducing a computer into the erection site was undertaken. To take the full advantage of using the latest machines of high performance, it was planned to utilize the computer to control several measurements which should be performed during erection as well as to calculate the optimum adjustment.

As the items to be measured, the followings may be considered.
- The cable tensions
- The bridge deck and pylon geometry
- The temperature distribution within a bridge superstructure
- The stress distribution within a bridge superstructure
- The forces required for the erection control

The system, the hardware and software, was built up taking account of the method and instruments required for the measurements of these items.

The way of the communication between man and machine is another important point to be considered. The speed and accuracy appear to be more important requirement than the flexibility so far as the system used on the site is concerned. From this point of view, the full attention was paid to the easiness in operation. Alpha-numerical input items were reduced whenever possible in order to avoid misoperation. Such equipments as color graphic displays were utilized positively for the clean presentation of the results. The programs for measurements were designed carefully so that they may help the site engineers who are not necessarily skilled in operating the measuring instruments.

The last point considered is the choice between the two types of program: (1) The program oriented to the particular bridge or (2) the program for general purpose. The former was chosen in the system described here because of easiness in both producing and operating the program, while the hardware was determined considering the future application. This naturally causes the serious problem that great efforts may be required to modify the program for the application to the other bridges. The system was thus designed for the erection of a specific bridge, Chichibu Bridge, though the basic concept appears to have generality.

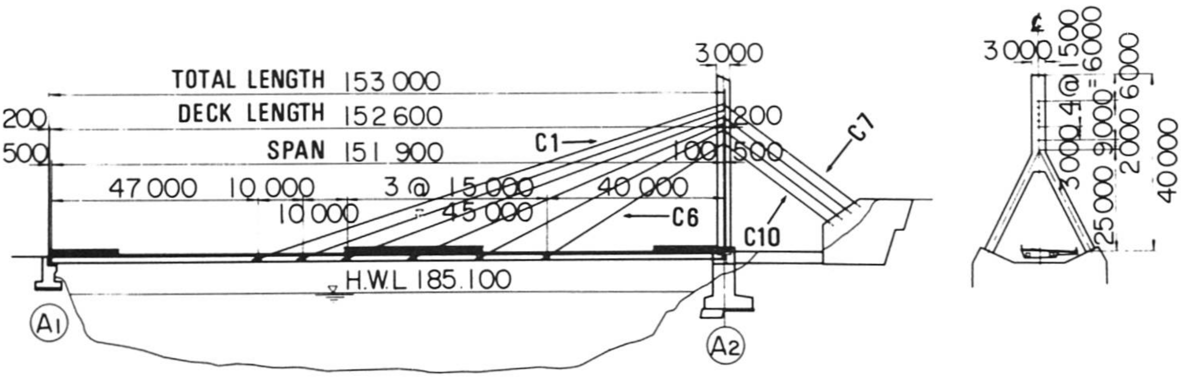


Fig. 1 Chichibu Bridge

Chichibu Bridge, Fig.1, is a highway bridge crossing Arakawa River with a single span of 151.9 m. It has 12 front stays arranged in two inclined planes in fan configuration and 4 parallel back stays in a single vertical plane. The superstructure was planned to be erected by cantilever method. As is the case with many similar precedents, the cable adjustment is carried out at each stage when the next cable is fixed to the tip of the cantilever by means of jacks and shim plates. Erection and adjustment proceed thus in a one way direction to reach the final stage. Since readjustment of the whole structure after the completion of erection is not intended to be made, intermediate adjustments should be the more accurate. Chichibu Bridge is being erected at present, March 1985, and therefore only the data during the initial stage of the erection are presented in this paper, though more useful information will be available in the near future.

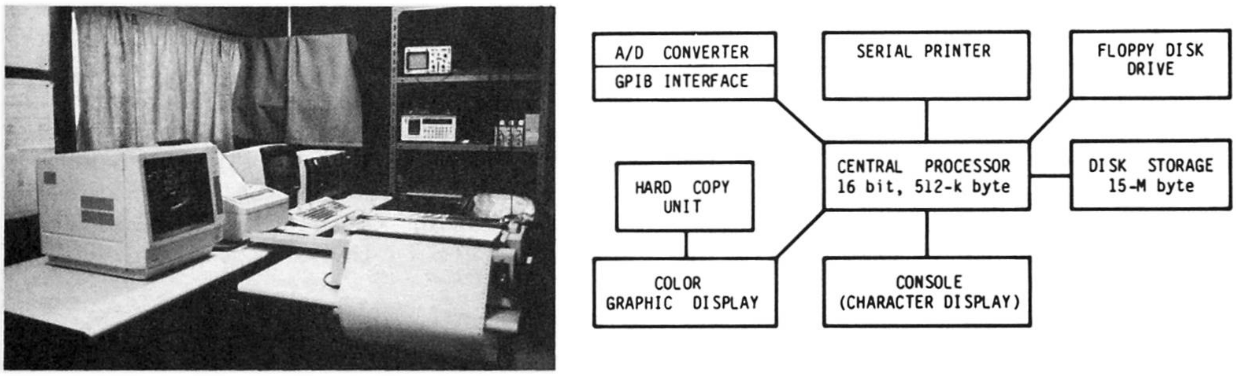


Fig. 2 Mini-computer system

4.2 Hardware Composition

The hardware illustrated in Fig.2 was chosen from commercially available machines. The central processor of 16-bit machine with 512-k byte memories and the 15-M byte disk storage are sufficient to execute the programs coded in Fortran. A floppy disk drive is required not only as an auxiliary storage but as the device that receives the influence matrices calculated using the space frame analysis program in a general purpose computer. An analog to digital converter is necessary for the measurement of cable tension by vibration method, the detail of which will be given in 4.3. A GPIB interface provides a means of the interactive operation between computer and digital measuring instruments. The CRT displays and the printer which are able to handle Japanese letters were employed from the standpoint of easiness in operation, since only the domestic use is scheduled for the present.

4.3 Measurement of Cable Tension

There are several methods for the measurement of cable tensions. The very fact that the measurement has been attempted in various manners appears to indicate the difficulty of measuring cable tensions.

In the system, the vibration method was chosen as a main method because of two reasons: (1) A long term measurement of the static phenomena is fairly difficult from the standpoints of both stability of measuring instruments and durability of transducers and (2) the measurement by the vibration method can be done whenever it is required with few preliminary works. In the vibration method, the tension is obtained from the natural frequency using the relationship between the frequency and tension of strings.

$$T = F_n^{2} \cdot (4 \cdot W \cdot L^{2}) / (n^{2} \cdot g) \quad \text{................(9)}$$

where T = the tension, F = the n-th natural frequency,
W = the weight per unit length, L = the cable length,
n = the order of natural vibration, and g = acceleration of gravity.
Since actual cables are not ideal strings but have some flexural stiffness, the tension given by Eq.(9) should be compensated by adequate means.

The natural frequencies are evaluated from Fourier spectra of the ambient vibration which is measured using servodrive accelerometers. Data acquisition and vibration analysis are made by the computer using analog to digital converter. The system determines by itself the parameters, sampling interval etc., according to the approximate frequency which can be foreseen from the required tension; otherwise the operator is required to be experienced in the vibration analysis since he should determine these parameters taking accout of Nyquist frequency, frequency resolution, etc.. The computed spectrum is presented on the graphic display, from which the significant frequency is chosen by positioning a hair cursor. It must be mentioned here that the spectra of ambient vibrations do not always exhibit sharp peaks which correspond to the natural frequencies because of the statistical instability of vibrations. Although the measurement of ambient vibrations has an advantage in that it does not require such particular devices as vibrators, this instability appears to be a rather serious problem which should be investigated and solved in future. Once the natural frequency is determined, the tension is calculated immediately using the cable characteristics stored preliminarily in the disk storage.

In order to compensate the effect of flexural stiffness of cables, the system is designed to use the tension derived from the jacking force as a standard value to be compared. The jacking force is obtained from the oil pressure by multiplying the section area of a piston. The pressure measurement should be accompanied by the measurement of socket movement to know the force at the very moment when the contact of a cable socket with an anchor block is broken. As is illustrated in Fig.3, the jacking force shows a sudden increase at a certain point as the pressure is increased gradually. In region A, the jack and anchorage cooperatively bear the force

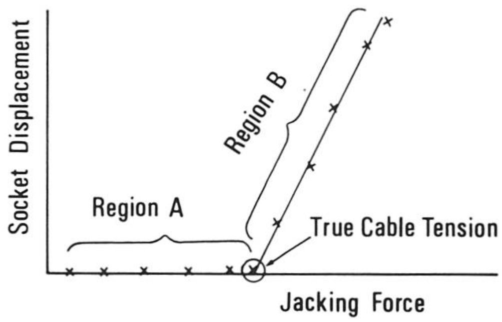


Fig. 3 Plot of Oil Pressure vs. Socket Displacement

which comes from the cable. In this region, the cable tension which is equal to the sum of jacking force and anchorage reaction is steady and the socket is hardly moved. If the jacking force exceeds the true tension (region B), the tension in the cable increases balancing with the jacking force and results in a remarkable socket displacement because of the axial stretch proportional to the excess tension. Consequently, the intersection of the line fitted to the data in region B and the horizontal axis in Fig.3 gives the true tension. This measurement is also conducted with the aid of the computer which accomplishes the real time display of measured values and the immediate determination of the tension.

The relationship between the two tensions, derived from the jacking force and vibration, is assumed to be constant and is to be used to compensate the effect of flexural stiffness when the tension is measured by the vibration method after the jack has been removed for the installation of the next cable.

4.4 Measurement of Bridge Deck and Pylon Geometry

The profile of bridge deck and the inclination of pylon were measured by traditional optical instruments, a level and transit, and the measured values were inputted alpha-numerically to the computer. Although the instruments called optical displacementmeters capable of providing analog output are commercially available, they are expensive and appear to be too sensitive for the site use. At present, there is little prospect of breaking this bottle-neck in the computer aided measurement.

4.5 Measurement of Temperature

The system has the function to measure ambient air temperature and the temperature distribution within a bridge superstructure. The prime objective of the temperature measurement is to obtain the data used in the calculation to cancel the thermal effect, though it is almost impossible to know the complex temperature distribution entirely. Therefore, the measurements of cable tensions etc. are desired to be conducted when the temperature distribution is nearly uniform so as to reduce the correction as small as possible.

Thus, to find the adequate condition for the measurement of cable tensions etc., the sufficient knowledge of thermal behavior of the structure is necessary. Since the phenomenon may be dominated by a number of factors, weather, season, the location of the bridge, etc., the daily changes in the temperature distributions should be observed in various conditions. The system performs the periodical measurement for this requirement according to the parameters inputted in advance, and represents the recorded distribution on the graphic display whenever required.

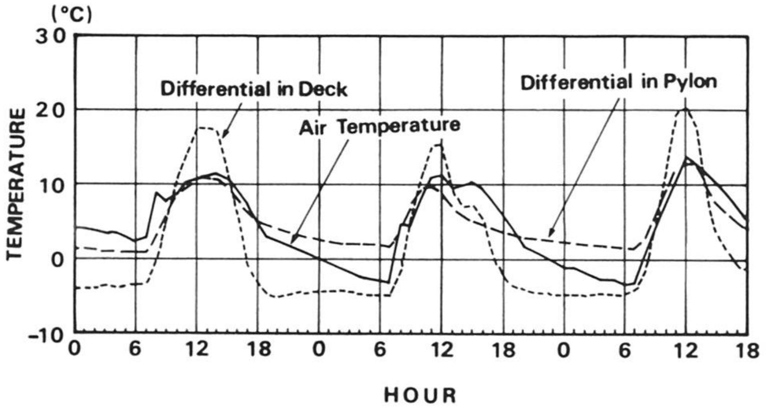


Fig. 4 Daily change in temperature

Fig.4 shows the typical daily change in temperature distribution measured on fine days in the winter, which reveals that the temperature difference between the top and bottom of the bridge deck reachs at a constant value at 7 p.m. while the ambient air temperature falls gradually throughout the night: this indicates that it is possible to start the measurement an hour after sunset.

4.6 Measurement of Strains

The system has the function to measure the strain in bridge deck and pylon. Although the measured values are not utilized directly in the calculation of the optimum adjustment, they are expected to help engineers providing the data which indicate the physical behavior of the structure. The measurement is performed whenever required, using strain gages and the digital strain meter which is controlled by the computer via GPIB interface. The stress distribution is represented on the graphic display as well as numerical outputs.

4.7 Calculation of Optimum Cable Adjustment

The calculation of optimum cable adjustment is the most elemental function of the system. Prior to the calculation, the measured responses are converted to those at the standard temperature, which is assumed to be 20°C of uniform distribution, in order to cancel the thermal effects. The tempratures at the very moments when the cable tensions etc. are measured are derived from the data measured periodically using interpolation technique. Then the optimum cable adjustment is calculated letting all weight coefficients be unity (Eq.8) and the residuals are predicted (Eq.3). Although this is the final goal that the computer can reach, it should be regarded as a standard adjustment which is proposed by the system. Further informations about the other adjustment can be obtained in two manners: (1) Changing the weights or (2) inputting directly arbitrary adjustment. This function allows engineers to determine the practical adjustment taking account of such factors as the minimum thickness of available shim-plates etc.. The computer carried out this calculation interacting with engineers, displaying the results immediately on the character display (Fig.5) as well as the graphic display (Fig.6). Thus the final adjustment is to be determined by the engineer, utilizing the data provided by the system.

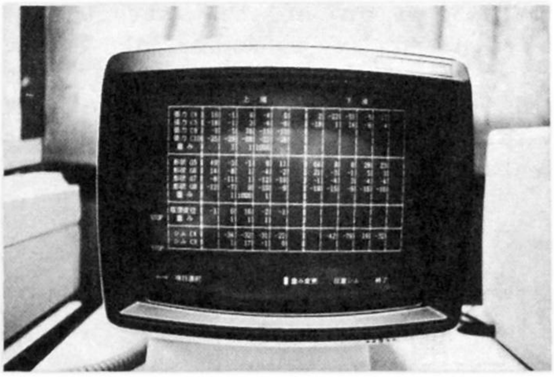


Fig. 5 Comparison of various adjustment displayed on the CRT

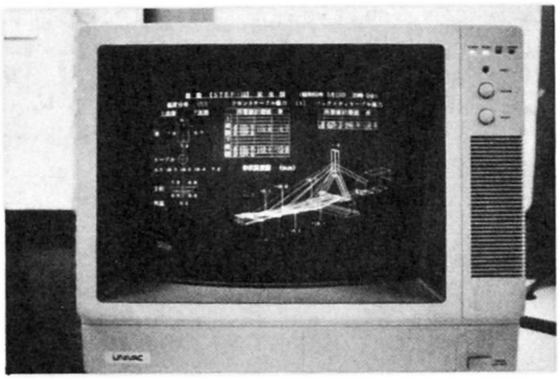
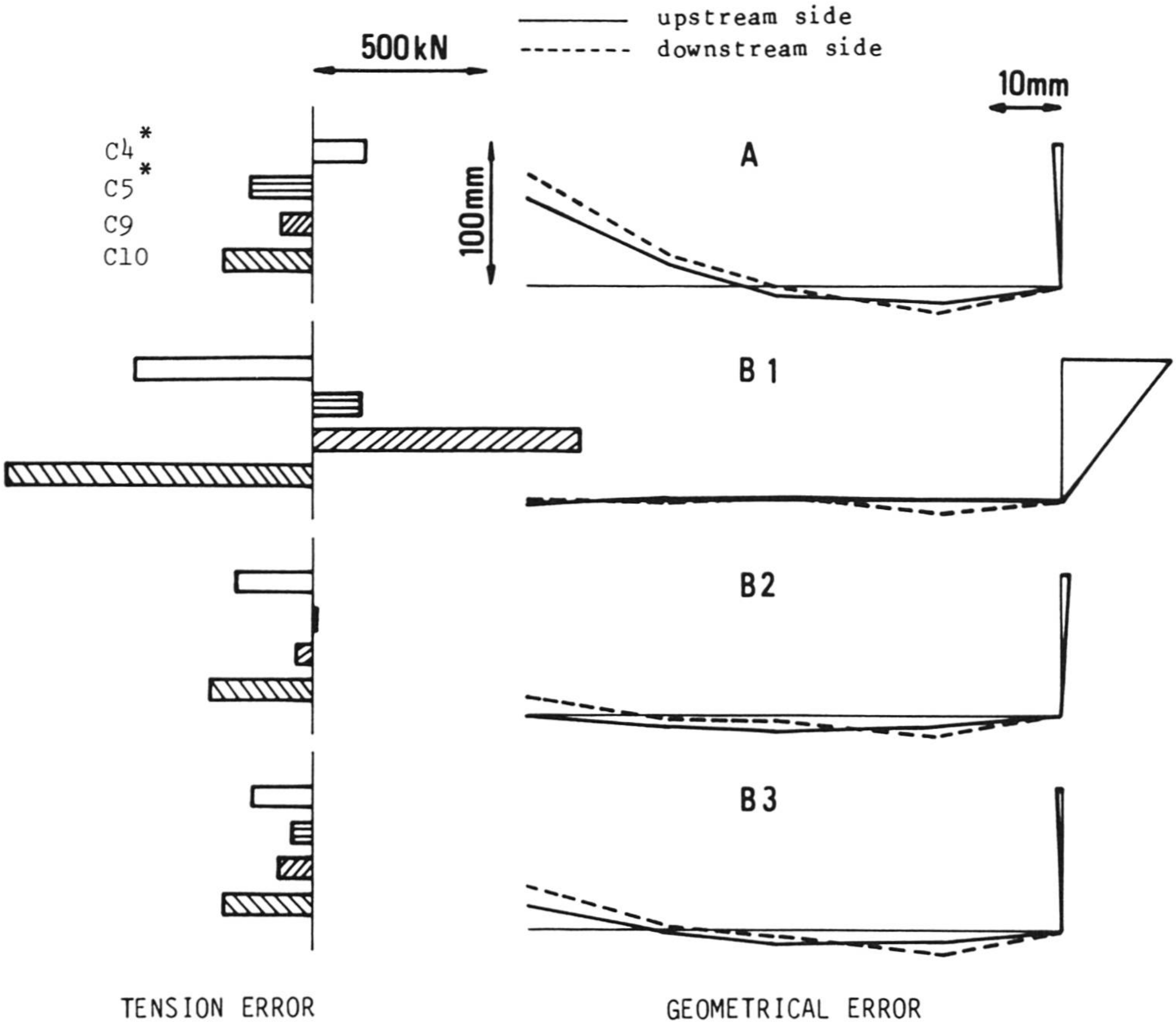


Fig. 6 State of the bridge structure represented intensively on the graphic display

The typical results of the calculation are shown in Fig.7. In this adjustment, only the upper two front stays as well as the upper back stay are adjusted, though the structure has 6 front stays and 2 back stays at this erection stage. The tension in the cables except C6 were measured since C6 are located relatively apart from C4, the lengths of which were adjusted.



* The larger one of the two residuals in the two front stays which are arranged in different planes with the same name is indicated.

A: Observed deviations before adjustment

B1 - B3: Predicted residuals

- B1: Biased weights are used to reduce the diviation in deck profile
- B2: The optimum adjustment (all weights are unity)
- B3: The adjustment chosen by the engineer

Fig. 7 A case example of cable adjustments

The measurement conducted before the adjustment exhibited that though the tension errors were relatively small, the deck profile deviated from the required one to some extent, and the proper adjustment was considered to be necessary (A). B1 shows the residual which is a result of the adjustment to reduce this deviation in the deck profile, using the biased weight coefficients. From the figure, it is obvious that the deck profile is corrected sufficiently, though this adjustment is not applicable since it causes marked residuals in the cable tension and pylon top displacement. This phenomenon can be foreseen theoretically. Since the biased weights reduce the "effective" number of items in vector D, the characteristics of the adjustment approach to those obtained from Eq.5. The proposed optimum adjustment (B2) reduces the deviations in the deck profile reasonably, while the tension error remains at the same order.

In fact, the adjustment slightly differed from the calculated optimum was applied finally (B3), since the engineer prefered the over-camber to under-one. This appears to be a good example of the limitation of the computer system. Although the system undoubtedly helps engineers to a great extent, it cannot take the place of experienced engineers. Therefore, in designing such system as described here, the flexibility which allows engineers to add their judgement is considered to be necessary.

5. CONCLUDING REMARKS

The actual responses of the cable-stayed bridge during erection were surveyed in relation to the cable length adjustment and it is concluded that the adjustment should be conducted in a manner to reduce the overall error in the structure whatever the causes may be. To accomplish the requirement, the method similar to the least square method was developed. For the utilization of this method, the mini-computer system was introduced into the erection site. The system was designed not only to execute the calculation of adjustments but to control the measurement required for erection.

Now, the system is being applied to the erection of Chichibu Bridge and some results of intermediate adjustments have been obtained. The results were in good agreement with the calculated responses and the proposed optimum adjustment reduced the overall error properly as it had been expected. Thus, the validity of the new method, which was investigated by the numerical simulation previously, was proved by the actual erection. These results appear to indicate also that (1) the measurements of cable tensions etc. and the compensation of the thermal effects were performed precisely and (2) the evaluation of the influence matrix, which is the theoretical basis of the proposed adjustment, was appropriate. It should be noted finally that the computer system can be a powerful tool from the standpoint of the labor-saving as well.

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All papers are written in Japanese.