ERECTING THE INCLINED PYLON LEGS IN A CABLE-STAYED BRIDGE WITH THE SUPPORT OF STRAIN AND STRESS ANALYSIS

Witold Prószyński[1], Andrzej Stańczyk[2]

[1]Institute of Applied Geodesy, [2]Roads and Bridges Institute,
Warsaw University of Technology, E-MAIL: wpr@gik.pw.edu.pl

Abstract

The paper sums up the authors' experience in guiding the axes of inclined pylon legs during the construction of the first two large cable-stayed bridges in Poland. To build such a structure it is necessary not only to obtain a designed shape of the legs but also to ensure a proper system of internal forces. A method of reaching this goal is presented. It consists in setting out and erecting the successive sections of each leg along the predicted momentary axis and correcting the shape and the force system in a structure by inserting straining beams in between the legs on several levels. While computing the momentary axes, the deflections due to both the loads and the rheological effects in concrete are taken into account. The necessity of close co-operation between a structural engineer and an engineering surveyor over the whole erection process is strongly emphasised.

1. Introduction

The problem of erecting the inclined pylon legs during the construction of the first two large cable-stayed bridges in Poland proved to be an interesting and challenging task both for structural engineers and engineering surveyors. To build such a structure it is necessary not only to obtain a designed shape and dimensions of the legs, but also to ensure a proper system of internal forces within the structure. During the construction process the structure was undergoing several „stress and strain" states, some of them being at the limit of carrying capacity, and it was the most essential objective for a structural engineer supported by an engineering surveyor to „navigate" the structure safely to reach the design state within the prescribed tolerances. A suitable erection strategy has been worked out to achieve this goal.

Contrary to routine setting out, instead of the fixed designed axes of the pylon legs the predicted momentary axes had to be set out. Adding to that the deformations of the structure due to external factors, the setting out had to be combined with deformation monitoring.

Although not based on the use of deformation monitoring model, it is a good example of close co-operation between engineering surveyors and structural engineers. The necessity of such co-operation results from the complexity of the task to be per-formed.

2. First large cable-stayed bridges in Poland - main features

The recent closer contacts established between Poland and the western countries and the resulting free access to European market (cables, anchorages) made it possible for Polish engineers to start the construction of large cable-stayed bridges. As such structures, and much larger, had successfully been built all over the world, the experiences we have gathered so far are perhaps not much innovative. However, hoping that there can be at least a few interesting elements in our work worthwhile to be disseminated among the engineering surveyors, we have decided to present our approach.

The first of the bridges, Świętokrzyski bridge located in the centre of Warsaw (further on referred to as bridge I) was put into use early October last year. The second – Sucharski bridge in Gdańsk (referred to as bridge II), the construction of which has recently been finished, will be

opened in October this year. Currently, the supports of the third bridge – Siekierkowski bridge in Warsaw (referred to as bridge III) are almost completed and the concreting of pylons has already been started. The builder of the pylons is the Polish Enterprise Warbud S.A. The bridge schemes are shown in Fig.1 and the shapes of the pylons – in Fig. 2 (see Stańczyk 2000b).
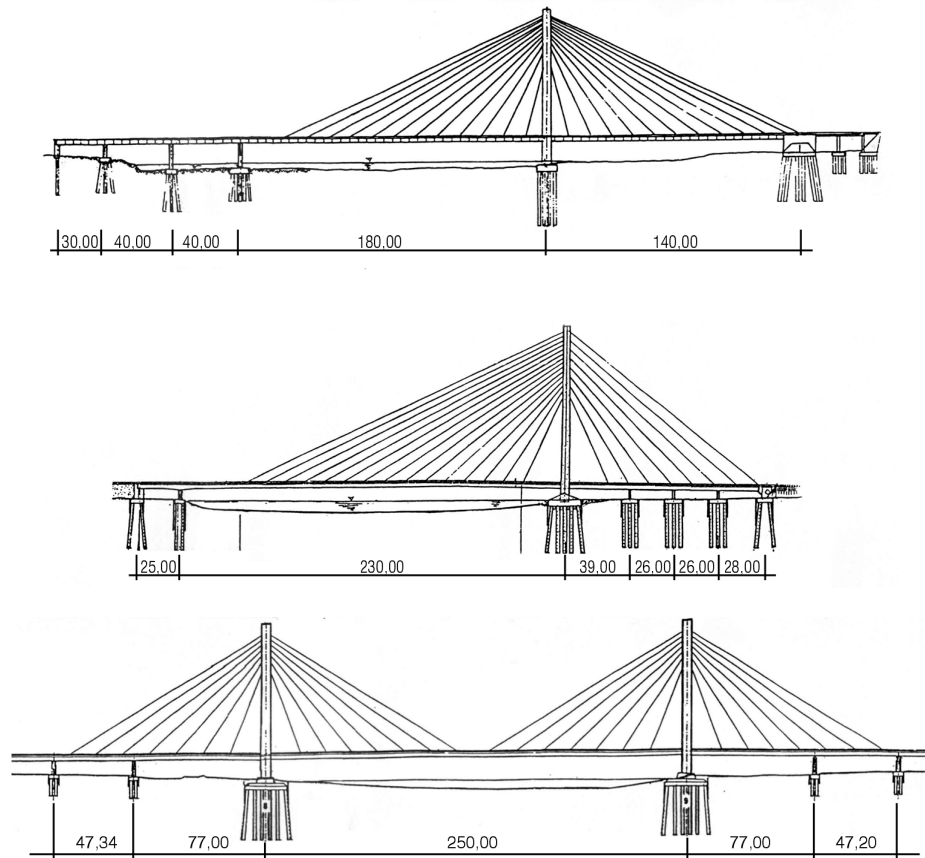
Fig.1. Schemes for cable-stayed bridges (distances in meters)

In their lower part the pylons of bridges I, II have inclined columns. The construction of the columns (called here – the legs) is the main subject of the present paper.
The same problems in guiding the pylon axes as in bridges I, II will be encountered for the pylons in bridge III, which, under their upper spandrel beams, also have inclined columns.
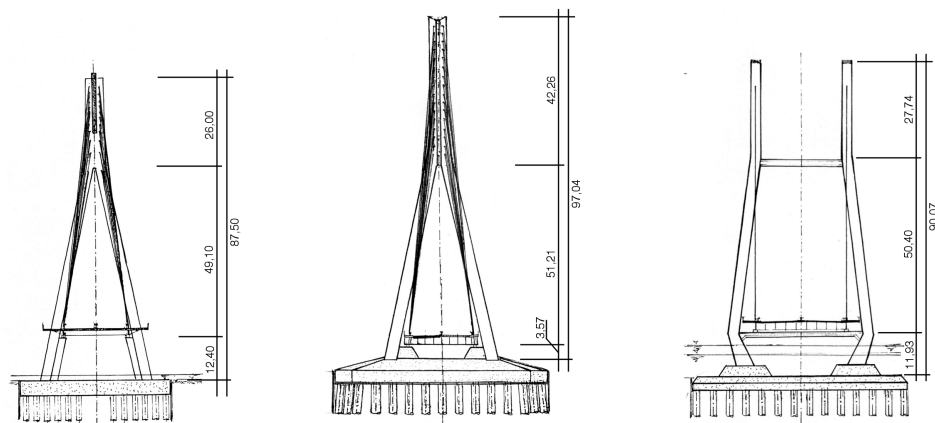
Fig.2. The shapes of the pylons (distances in meters)

The pylons of bridges I, II were erected in sections (each about 4.20m high) with the use of shuttering:
- for the first three sections: the stationary shuttering supported on the foundation slab of the pylon;
- for other sections: a self-climbing shuttering PERI.

In the erection process of the inclined pylon legs the straining beams were used at three levels, preventing the structure from the loss of bearing capacity and also used for correcting the geometry and stresses within the structure.

The successive phases of the erection process for bridges I, II are shown in Figure 3.
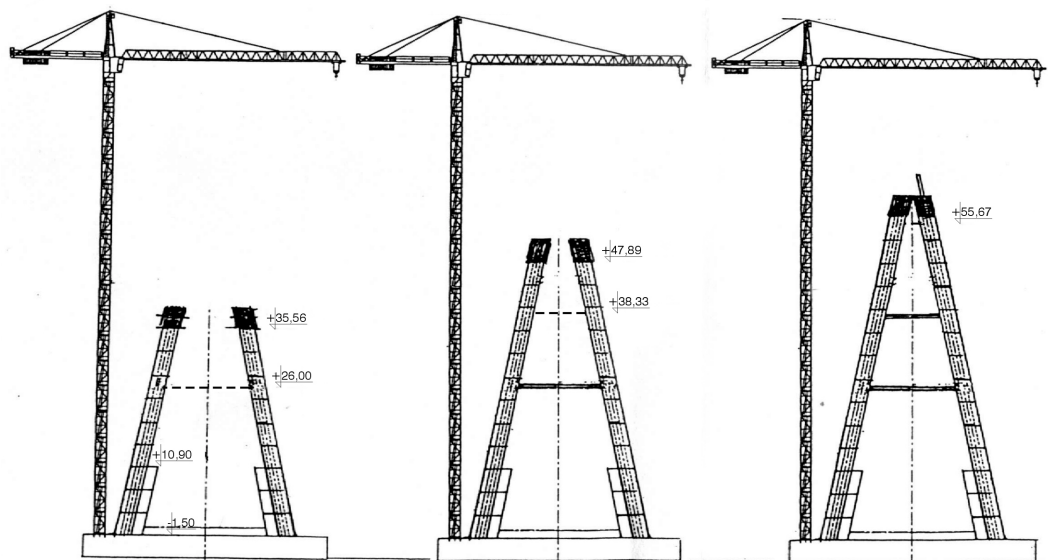

Fig.3. The phases of the erection process

The deviations from the straight line for the axis of each inclined leg in the as-built pylon were specified by the designers as ±10mm.

3. Analysis of the behaviour of inclined pylon legs during their erection

At the very beginning of the analysis it was observed that the most difficult phase of the pylon erection would be the erection of its inclined legs, until they form a rigid frame in their plane. Besides the requirement that the final shape should comply with the designed shape, it is necessary to obtain a system of internal forces sufficiently close to that anticipated in design computations, or even a more advantageous one. This concerns the forces from the loads increasing during the erection of legs and also from the intended or random deformations of these structures. That is why this erection phase has been subjected to a detailed static and strength analysis (see Stańczyk 2000a).

In the analyses for bridges I, II the following elements were taken into account:
- loads acting upon a structure, such as: the weight of successive sections, the weight of shuttering with their equipment, wind pressure, temperature changes;
- deformations (deflections) of the structure, such as: those due to the loads mentioned above, those due to concrete creep and the deformations caused by possible use of straining beams.

The analysis showed that as early as in the erection process there appear in the extremely strenuous cross-sections the limit states of the structure, such as:

- scratches in concrete in the tension zone of a cross-section or the crevices in the contact area between the neighbouring sections, where concretes of different ages meet;
- surpassing the bearing capacity of a cross-section, that is to say, the structure failure.

In consequence of the above observations it turned out necessary to provide temporary straining beams at three intermediate levels (see Fig.3). The levels were calculated with the assumption that installing and expanding of each straining beam should take place at such a phase of the erection process when constructing the successive leg section might cause the threat of the occurrence of scratches or crevices in the structure. It was further assumed that each straining beam will be expanded with a force such that the deflected leg axis at this level can be brought to its design position (see Fig. 4). After joining the legs in a frame and removing the straining beams, the leg axis is supposed to assume a designed shape throughout its length, within the specified tolerance.
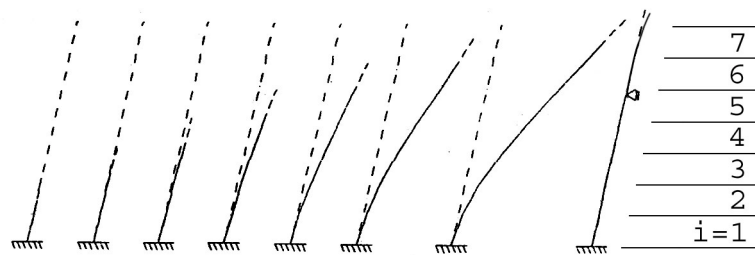

Fig.4. The shape of the leg axis before and after expanding the first straining beam (bridge II)

4. A strategy for guiding the erection of inclined pylon legs

Initially, it was planned to erect each new section so that its axis is tangent to that of the last completed section. In preliminary discussions with the builders of bridge I the surveyors expressed their apprehension that due to cumulation of errors induced by the erection technology, this procedure may result in excessively large deviations of the top sections, exceeding the deviations computed on the basis of stress and strain analysis.

Next, a modification of the above procedure was suggested. It consisted in:

- monitoring the positions of shuttering for a new section in several characteristic phases such as: after provisional assembly, after final tightening, before and after concreting;
- filtering out analytically the resulting dislocations and deformations of shuttering in order to obtain a momentary leg axis undisturbed by the inaccuracies induced by the erection process.

The extension of this computational axis was to be taken as a reference for setting out the next section. This procedure would be rather complicated and due to the influence of additional disturbing factors (e.g. temperature, wind), it would require almost continuous monitoring of the structure. Therefore it was rejected as uneconomical.

Finally, as a reference for setting out the axis of each new section before installing the first straining beam a predicted momentary leg axis was accepted (see sect. 5). It is the axis of a leg deflected due to the weight of the structure, the weight of shuttering and also due to concrete creep.

By expanding the installed straining beam, the appropriate corrections of the legs axes were made to reach the theoretical shape. The magnitudes of these corrections were calculated on the basis of the currently carried out strain and stress analysis.

This procedure was repeated for higher segments of the structure till the legs met together forming a frame.

Owing to the adopted strategy of guiding the axes of inclined pylon legs with the support of strain and stress analysis it was possible to obtain the deviations of each leg within the specified interval ±10mm and also to reduce the extreme residual stresses in the structure. The success of this strategy is also due to a close and sometimes very intensive co-operation between a structural engineer and an engineering surveyor.

5. The deflection model and its accuracy

The formula describing the momentary leg axis for the k-th section (see Fig.5) in the pylons of bridges I, II is:

$$u_{k,t} = u_k + \Delta u_k (t, \tau) \tag{1}$$

where:

$u_{k,t}$ - deflection of the momentary leg axis at the top of the k-th section;

u_k - short term deflection due to the weight of the structure itself, the weight of shuttering and its equipment, determined on the basis of elasticity theory;

$\Delta u_k (t,\tau)$ - deflection increment due to concrete creep, increasing in time exponentially

t   - age of concrete for successive leg sections;

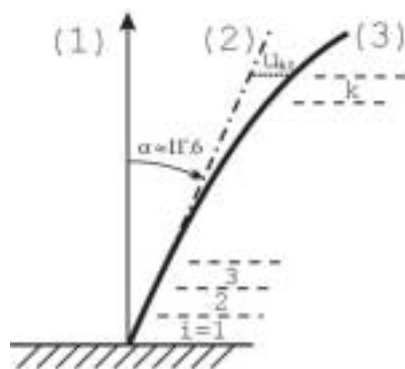τ - the acting time of successive loads for each section.

Fig.5. The deflection of the momentary leg axis (3) from the theoretical axis (2), inclined with respect to a vertical line (1).

$$u_k = \sum_{i=1}^{k} \int_{s=0}^{4.20} \frac{M_1 M}{E_i J(s)} ds + \sum_{i=1}^{k} \int_{s=0}^{4.20} \frac{N_1 N}{E_i A(s)} ds + \sum_{i=1}^{k} \int_{s=0}^{4.20} \frac{T_1 T}{G_i A(s)} ds + ... \tag{1a}$$

where: i - number of the section; M_1, N_1, T_1 - the bending moments, the axial forces and the shearing forces, each caused by the unit force, applied to the top of the momentary leg axis and directed horizontally towards the pylon axis; M, N, T - the quantities as above, each caused by the actual load (here – the weight of the structure and that of the shuttering); A(s), J(s) – geometrical parameters of the leg cross-sections; E_i, G_i - material parameters.

The omitted part of formula (1a) contains terms expressing the influence of torsion moments and effects of temperature variation. The value of the first term is usually dominating and determines the value of short-term deflection. The remaining terms are negligibly small, although for some cases of external effects they may assume significant values.

Instead of presenting the formula for the second component in a model (1) we shall only note, that due to large cross-sectional dimensions, high rate of construction works and the progressive increase in load till the installation of a straining beam, the value of this component did not exceed 1% of the whole deflection.

As an example, Table 1 shows the values of $u_{k,t}$ for bridge I for the moment of completion of section 6 and for the moment preceding the installation of the first straining beam at a level of section 7. To obtain a space necessary to accommodate the straining beam, two higher sections, i.e. 8 and 9, had to be erected and the shuttering raised to the level of section 10.

Table 1

Values of $u_{k,t}$ [mm] for the top of the i-th section										
i	1	2	3	4	5	6	7	8	9	10
$u_{k,t}$	0.3	0.9	1.8	2.9	4.3	5.7	-	-	-	-
$u_{k,t}$	0.7	2.1	4.2	7.4	11.7	17.0	23.1	28.0	35.9	42.2

The accuracy of the predicted momentary deflection depends on the accuracy of the individual parameters and coefficients in a model (1). The accuracy assessment of this prediction is a complex problem. Here, we shall only touch on some of the sources of discrepancies between the model deflections and the actual on-site deflections:

i.   In spite of the broad knowledge in the area of concrete technology the required „strength and deformation" characteristics are obtained on site within a certain tolerance. The values which we get from the in-situ samples differ even within one leg section;

ii.   The process of concrete creep is fairly well-known for the compressed concrete but much less-known for the concrete under tension. Whilst, during the erection, the extreme stresses in the compression zone of the leg cross-section are far from the compression strength, in a part under tension they are close to the tensile strength;

iii.   The actual erection time-schedule often differs from the planned one;

iv.   The geometrical parameters of the pylon leg may change after a possible occurrence of scratches in the concrete or crevices in the contact area between the neighbouring leg sections. This results in a significant decrease in the moment of inertia of a cross-section, and consequently, in the dramatic increase of deflections.

6. Obstacles in applying a dynamic deformation-monitoring model

After the erection process was started and the first 3 bottom sections of the pylon legs (in bridge I) had been successfully completed an analysis was carried out as to the possibility of constructing and applying in practice a dynamic deformation-monitoring model meant as a tool for guiding the axes of the pylon legs. Strictly speaking, the aim was to improve the accuracy of predicting the momentary leg axis.

Several obstacles have been found, which made the idea of such a model unfeasible. Most of them are the factors, which are difficult to be modelled. Below, we shall list them and give a brief explanation for each item:

-   too few measurements to form a sufficient set of data powerful enough to improve the structural engineer's knowledge of the actual values of model parameters;

-   the observational schedule was determined to a large extent by the economical factors and the needs of the erection technology. The same applies to the adopted accuracy level of the measurements;

-   additionally, for bridge I, every two newly completed top sections in both the legs were not available for geodetic observations because of a special cover which was applied in order to secure a uniform distribution of temperature in a leg's cross-section.

-   exerting a pressure upon the structure through each of the straining beams, brings about a new „stress and strain" state of the structure and changes the starting point for modelling the behaviour of the next part to be erected;

-   the external factors (such as wind, temperature irregularities within the structure, dynamic loads from the crane anchored to the structure), which can significantly disturb the axis of a pylon leg, are difficult to be modelled and hence cannot be incorporated in a model;

- the deviations in positioning and tightening of the shuttering, having a random nature, are difficult to model;
- dislocations and deformations of shuttering due to dynamic loads induced by the process of placing the concrete, having a complex random nature, are also difficult to be modelled;
- significant time-differences in concreting the corresponding sections of both the pylon legs, caused by the unexpected situations or difficulties occurring on site. This may result in the asymmetry of the structure's strain and stress responses to expanding each of the straining beams.

A dynamic deformation-monitoring model could be more feasible, for instance in investigating the behaviour of a completed structure under the influence of external factors, provided that a sufficient number of appropriately accurate observations could be carried out.

7. The setting out and monitoring surveys - the disturbing factors

All the surveys for the erection of the pylons in bridges I, II were carried out by the Warsaw Surveying Company, specialising in the surveys for the needs of civil and building engineering (Przywara 2000, Stasiewicz, Prószyński 2000).

For each of the bridges the setting out and monitoring network was established as a classical angular-linear network tied up to the main survey control. Its points were chosen so that most of them might later serve as instrument stations for observing the pylon in all the phases of its erection. The network was measured by means of electronic total station Leica TCA 2003. The a priori standard deviations were assumed 1mm for distances and 0.5mgon for angles. It was adjusted as a local network and transformed without scale distortion (3-parameter transformation) into the points of the main survey control established earlier by another surveying company. A large (and perhaps excessively large) number of observations made in each of the setting out and monitoring networks resulted in an extremely high level of their internal reliability, the reliability measure reaching 0.90 and 0.95 respectively. With this reliability level the outliers were detected and located easily in successive LS-estimation rounds. This proved the opinion that in a model with a high reliability level the LS estimation can be an efficient diagnostic tool. Heights of the network points were determined by semi-precision levelling.

The measuring points on shuttering and on the completed part of the structure were observed from the points of the setting out and monitoring network and occasion-ally from the free stations, mostly with the use of the 3D polar method. As targets the stick-on reflective tapes and prism reflectors were used. The redundancy requirements were carefully obeyed both in setting out the positions of shuttering and in monitoring the movements of the structure. The automatic target recognition facility (ATR) in the Leica's TCA 2003 made it possible to find the reflector in a crowd of reinforcement rods and measure on a foggy day and at night.

For monitoring the vertical displacements of the pylon's foundation and those of other supports a precise levelling network has been established and measured periodically.

The influence of external factors (temperature changes, wind operation) upon the geometry of the structure made the surveyor's work difficult, both in setting out the position of shuttering for a new section and in checking the as-built part of the structure. Through additional monitoring surveys some rough estimations of the magnitude and character of this influence were made. On this basis the appropriate corrections were introduced to the determined X, Y, H positions to eliminate (or at least – to reduce) their distortions caused by the external factors mentioned above.

8. Concluding remarks

When planning the erection procedure for inclined pylon legs it is necessary to study the behaviour of the structure in all the characteristic intermediate stages of its erection process. Although the main framework of the procedure should be worked out by a structural engineer

on the basis of stress and strain analysis, the detailed scheme settling the scope of the setting out and monitoring work should be carried out in a close co-operation with an engineering surveyor. In addition to monitoring the vertical displacements of the pylon's foundation, the monitoring of horizontal deflections of each leg (at least of its top sections) due to the influence of external factors (wind, temperature changes, the loads exerted by crane) is an indispensable support for the setting out surveys.

The experience gained on bridges I, II is now utilised in the construction of the second cable-stayed bridge in Warsaw (bridge III).

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