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Determination of design moments in bridges constructed with a movable scaffolding system (MSS)

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Abstract

This paper introduces simple but effective equations to calculate the dead load and tendon moments in concrete box-girder bridges constructed with a movable scaffolding system (MSS). Through time-dependent analyses of concrete box-girder bridges considering the construction sequence and creep deformation of concrete, structural responses related to the member forces are reviewed. On the basis of the compatibility condition and equilibrium equation at every construction stage, basic equations that can describe the moment variation with time in movable scaffolding construction are derived. These equations are then extended to take into account the moment variation according to changes in the construction steps. By using the introduced relations, the design moment and its variation over time can easily be obtained with only the elastic analysis results and without additional time-dependent analyses considering the construction sequences. In addition, the design moments determined by the introduced equations are compared with the results from a rigorous numerical analysis with the objective of establishing the relative efficiencies of the introduced equations.

Keywords: Movable scaffolding system; Concrete box-girder bridges; Construction sequence; Creep; Dead load moment; Tendon moment

1. Introduction

In accordance with the increased demand for the construction of bridges, numerous bridges with exceptional aesthetics and style have been constructed. At the same time, the construction methods have also undergone refinement. In particular, among these construction methods, the movable scaffolding system has recently been recognized as one of the most efficient methods in constructing multi-span continuous bridges with an identical span length. This method has great advantages over other types of construction, particularly in urban areas where temporary shoring would disrupt traffic and services below [19]. However, the design and analysis of bridges constructed with the movable scaffolding system (MSS) require a consideration of the internal moment redistribution that takes place over the service life of a structure, on account of the time-dependent deformations of concrete, stress relaxation of tendons and changes in the structural system repeated during construction. Hence, in order to preserve the safety and serviceability of the bridge, an analysis that considers the construction sequence must be performed. All of the related bridge design codes [1,5] have also noted the need to consider the internal moment redistribution due to the time-dependent deformations of materials when the structural system is changed during construction.

Several studies have dealt with the general topics of design and analysis of bridges, while a few studies have been directed toward the analysis of the deflection and internal moment redistribution in bridges constructed by a movable scaffolding system [17,18]. Furthermore, development of sophisticated computer programs for the analysis of bridges considering the time-dependent deformations in addition to the construction sequence has followed, and

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a number of these programs are popularly used in the design practice [7–10].

Most analysis programs, however, have some limitations in term of a wider use stemming from complexities in practical applications, such as the preparation for a great amount of input data, no standard for the I/O formats, and a misunderstanding of output results. Consequently, a simple formula for estimating the internal moment redistribution due to the time-dependent deformations of concrete and the stress relaxation of the appropriate tendon used by the design engineer during the primary design of bridges is needed. Trost and Wolff [18] introduced a simple formula that can simulate the internal moment redistribution with a superposition of the elastic moments occurring at each construction step. A similar approach has been presented by the prestressed concrete institute (PCI) and the post-tensioning institute (PTI) on the basis of the force equilibrium and the rotation compatibility at the connecting point [3]; however, these formulas do not adequately address the changing structural system due to several adopted simplifying assumptions.

In this paper, simple but effective formulas that can calculate the internal moment redistribution in concrete bridges after completion of construction by MSS are introduced. With previously developed computer programs [11–15], many parametric studies for bridges erected by a movable scaffolding system are conducted, and correlation studies between the obtained numerical results and those by the introduced formulas are included to verify the applicability of the introduced formulas. Finally, a reasonable guideline to determine the internal design moments, which are essential in selecting a proper initial section, is proposed.

2. Construction sequence analysis

2.1. Construction sequences

Every nonlinear analysis algorithm consists of four basic steps: a formulation of the current stiffness matrix, a solution of the equilibrium equations for the displacement increments, stress determination of all elements in the model, and a convergence check. Several papers [11–15] have presented an analytical model that predicts the time-dependent behavior of bridge structures. Experimental verification and correlation studies between analytical and field testing results were conducted to verify the efficiency of the proposed numerical model. The rigorous time dependent analyses in this paper are performed with the introduced analytical model. Details of the analytical model can be found in the aforementioned papers [11–15]. In advance, all the material properties related to a tendon, from the definition of the stress–strain relation to the formulation of relaxation, can also be found elsewhere [11,12].

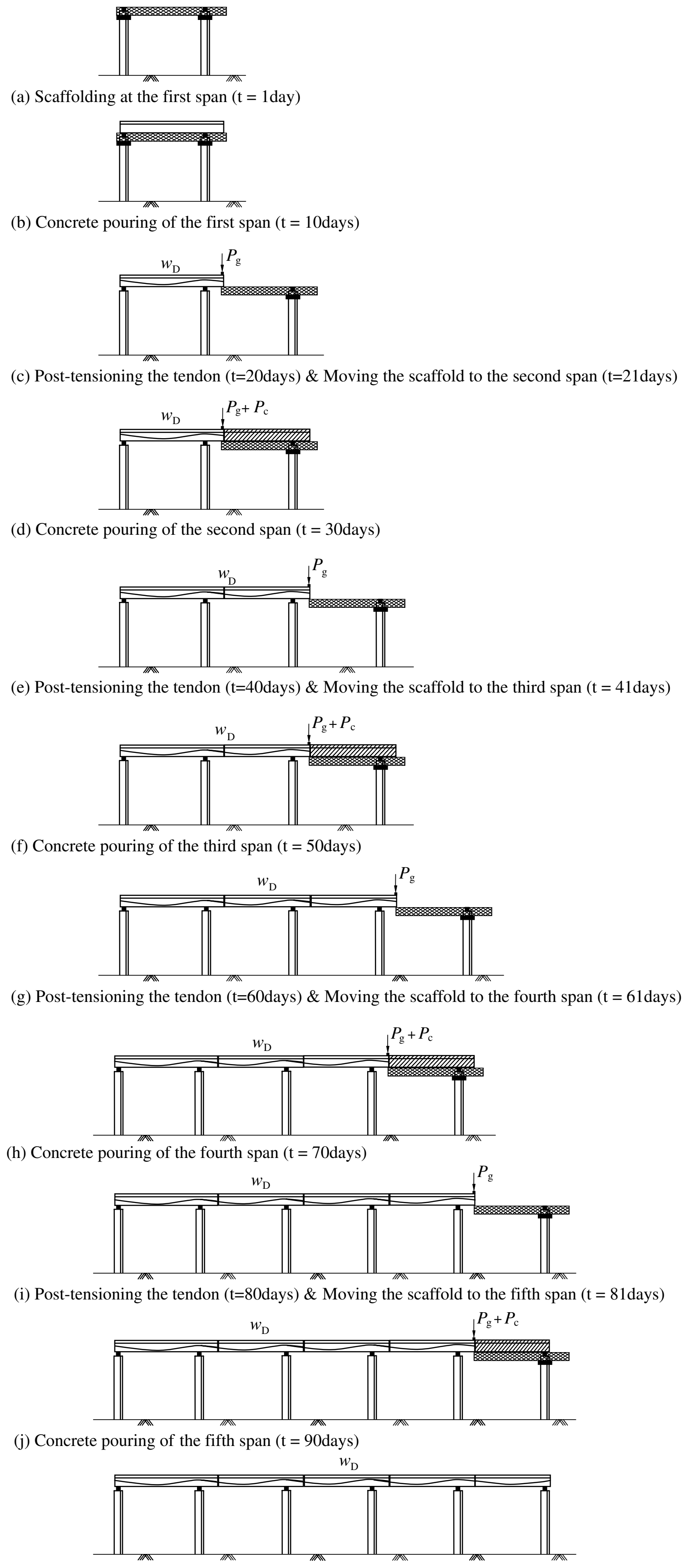
Movable scaffolding construction refers to a step-by-step construction of a bridge superstructure sequentially from the first to the end span using a movable scaffolding system, wherein each span of the superstructure is tied to a previous span by a sequential post-tensioning of tendons. The same erection process is repeated until the structure is completed; consequently, the internal moment is continuously changed according to the construction sequence and the changing structural system during construction. This signifies that the tendon force and the dead load dominantly affect the internal moment variation, as these two force components accompany the secondary moments caused by concrete creep deformation as the structural system changes. With consideration of the aforementioned factors, a five-span continuous bridge, shown in Fig. 1, was selected as an example structure in order to review structural responses due to changes in the construction sequences. This bridge has a total length of 150 m with equal span lengths of 30 m, maintaining a prismatic box-girder section along the span length. The assumed material and section properties are taken from an actual bridge; these are summarized in Table 1, and the tendon properties are presented in Table 2. The creep deformation of concrete is considered on the basis of the ACI model with an ultimate creep coefficient of $\phi_{cr}^{\infty} = 2.35$ [2].

As shown in Fig. 1, the time interval between each construction step is assumed to be approximately 10 days. When a scaffold moves to the next span, the concentrated load P_g caused by the self-weight of the scaffold acts at the end of the previous span (see Fig. 1(c), (e), (g) and (i)). In advance, an additional concentrated load P_c by the concrete pouring of the following span also acts at the same point. These repeated applications of concentrated loads, as shown in Fig. 1, continue until the end of the construction. If the self-weights of the scaffold and superstructure are assumed to be $w_g = 13.7$ ton/m and $w_D = 26.65$ ton/m, respectively, the concentrated loads of P_g and P_c can then be determined by the following equation derived on the basis of the moment equilibrium to the pier in Fig. 2, where the lengths of $L = 30$ m, $l_0 = 2.5$ m, $l_1 = 27$ m, $l_2 = 3$ m, $l_3 = 27.5$ m, and $l_4 = 6$ m are assumed in this paper by referring to an actual bridge project. The two concentrated loads of $P_g = 179.4$ ton and $P_c = 348.9$ ton are finally calculated in this example structure

$$P_g = w_g(l_3^2 - l_4^2)/(2l_3), \quad P_c = w_D(l_3^2 - l_4^2)/(2l_3) \tag{1}$$

2.2. Dead load moment variation

The dead load moments corresponding to each construction sequence at typical construction steps are shown in Fig. 3, where TS (total structure) in Fig. 3(c) indicates that all of the spans are constructed simultaneously at the reference time $t = 0$ day. As shown in Fig. 3(a), the dead load at the first span with a concentrated load P_g by the formwork for concreting of the second span (see Fig. 1(c)) produces a constant moment distribution without any change until the additional concentrated load P_c is applied at $t = 21$ days (see Fig. 1(d)). No internal moment redistribution by creep deformation of concrete in a span



(a) Scaffolding at the first span (t = 1day)

(b) Concrete pouring of the first span (t = 10days)

(c) Post-tensioning the tendon (t=20days) & Moving the scaffold to the second span (t=21days)

(d) Concrete pouring of the second span (t = 30days)

(e) Post-tensioning the tendon (t=40days) & Moving the scaffold to the third span (t = 41days)

(f) Concrete pouring of the third span (t = 50days)

(g) Post-tensioning the tendon (t=60days) & Moving the scaffold to the fourth span (t = 61days)

(h) Concrete pouring of the fourth span (t = 70days)

(i) Post-tensioning the tendon (t=80days) & Moving the scaffold to the fifth span (t = 81days)

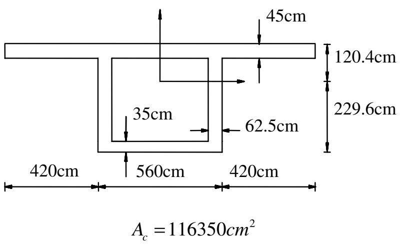
(j) Concrete pouring of the fifth span (t = 90days)

(k) Post-tensioning the tendon (t=100days) & Completion of the superstructure (t = 101days)

Fig. 1. Construction Sequences in a Bridge Constructed by MSS.

Table 1
Material and sectional properties used in application

Representative section properties



Material properties	
W_D	26.65 ton/m
f'_c	400 kg/cm^2
f_{sy}	4000 kg/cm^2
E_S	2.1×10^6 kg/cm^2

Table 2
Tendon properties used in application

P_i	A_P	f_{py}
1480 ton	106.4 cm^2	14765 kg/cm^2

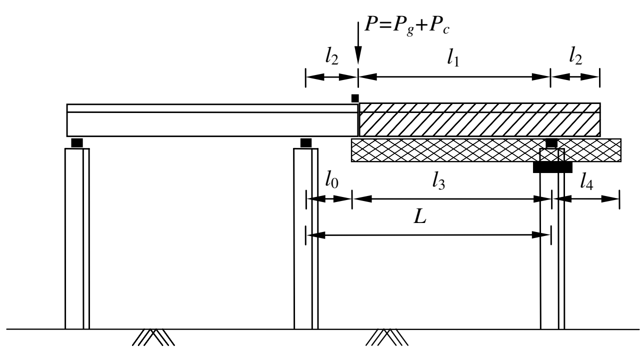


Fig. 2. Determination of concentrated loads, P_g and P_c.

occurs from $t = 21$ days to $t = 30$ days, as the structural system maintains the statically determinate structure.

The sequential applications of the dead load by the self-weight of the following span with the concentrated loads of P_g and P_c introduce repeated increases and decreases of the moment distribution along the span. A time dependent moment redistribution is also expected as the structural system changes in the statically indeterminate structure. However, the relatively short duration of 11 days and the subsequent application of a concentrated load P_c do not allow the time-dependent moment redistribution to be sustained. From Fig. 3(c), representing the final moment distributions after the completion of construction, it can be inferred that the dead load moment distribution is not greatly affected by the time-dependent deformations of concrete but is instead influenced by the concentrated load P_g and P_c. That is, the dead load design moment in a bridge constructed by MSS can be determined on the basis of an elastic analysis considering only the construction sequence.

Numerous parametric studies have been conducted with changes in design parameters such as the construction time interval and the ultimate creep coefficient Cu, which affect the time-dependent behavior of a structure, and a few typical moment envelope curves obtained by connecting the maximum moments experienced during construction at each point are presented in Fig. 4. These obtained results clearly demonstrate that the dead load design moment can be determined by an elastic analysis if only the construction sequence is taken into account.

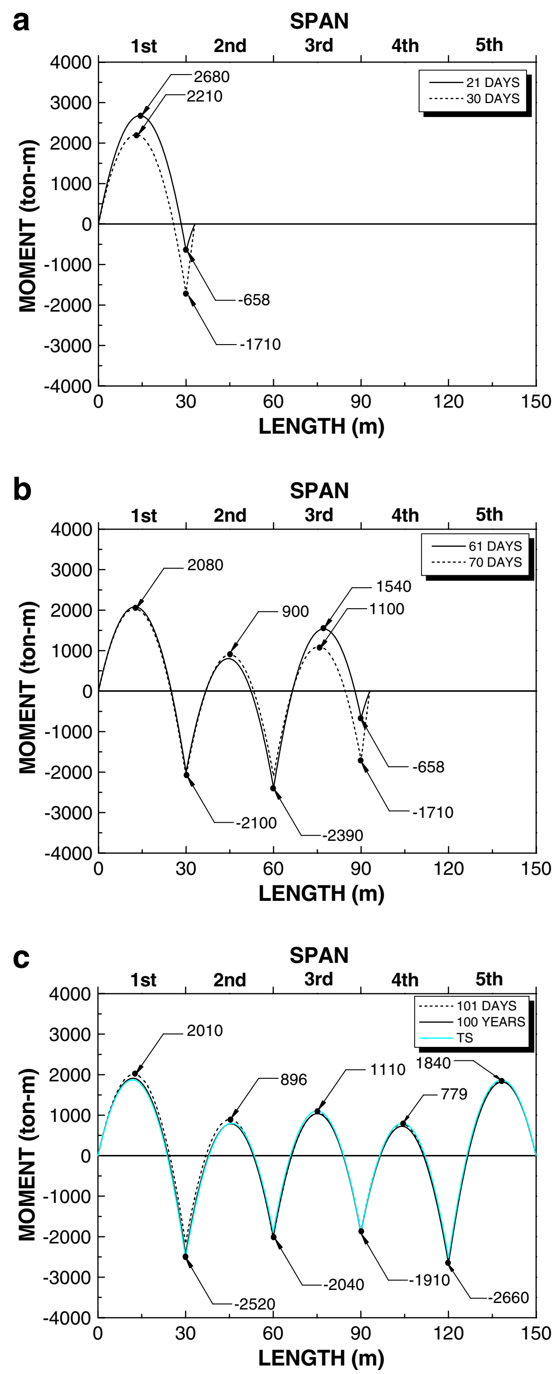


Fig. 3. Dead load moment distributions: (a) after construction of the first span, (b) after construction of the third span and (c) after completion of the bridge.

2.3. Tendon moment variation

The same example structure is also reanalyzed with respect to the longitudinal tendons. Referring to drawings

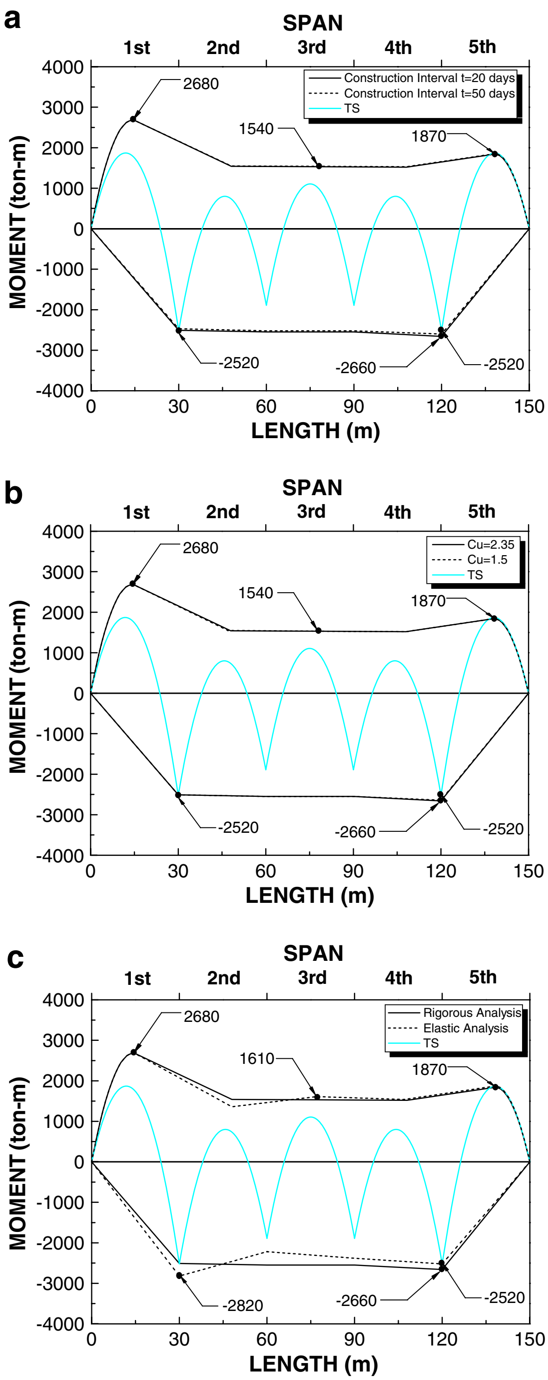


Fig. 4. Dead load moment envelopes for the example structure: (a) moment envelopes according to the construction time intervals, (b) moment envelopes according to the ultimate creep coefficients and (c) moment envelopes according to the analysis methods.

for a high-speed railway bridge project in Korea, the tendon profile shown in Fig. 5 is determined, and the stress relaxation in a tendon with time is taken into consideration on the basis of an equation proposed by Magura et al. [16]. As post-tensioning of the tendons must follow the construction sequences described in Fig. 1, the time interval for the continuity of tendons placed at each span is automatically determined. The example structure in Fig. 1 represents a time interval of $t = 20$ days after post-tensioning the tendons for the first span at $t = 21$ days when the first span works as an elastic body. As no additional post-tensioning is conducted at the second span up to $t = 40$ days, the moment variation from $t = 21$ days to $t = 40$ days, as shown in Fig. 6(a), is caused by the stress relaxation of the tendons post-tensioned at the first span.

As shown in Fig. 6, the moment distribution at time t represents a difference from that of the total structure (TS in Fig. 6) due to the changes in the structural system and the accompanying time-dependent effects of the concrete and the tendons at each construction step. In advance, the positive moments at the interior supports do not display a large variation while the negative moments at the mid-spans show definite decreases with time. This variation can be explained by the following: (1) The creep moment distributions in Fig. 7(a) shows that the creep moments represent the positive moment distributions along the entire spans and change with time even after completion of the bridge. The creep moment has a maximum value at the first interior support, whose value converges to $513t - m$ at the end of the time-dependent behavior; (2) the tendon moments as shown in Fig. 6 displays positive values at the interior supports and negative values at the mid-spans due to the primary tendon profile shown in Fig. 5. As the stress relaxation represents the reduction of the tendon forces with time, the moment values resulting from the stress relaxation have opposite signs to those noted above, which signifies that the moment reduction occurs along the entire span. Fig. 7(b) shows the moment reductions of the example structure according to the relaxation; (3) finally, the superposition of both moment components in Fig. 7(a) and (b) gives an increase of positive moments at the mid-spans and an immaterial variation of negative moments at the interior supports, which results in decreases of the tendon moments at the mid-spans. From the obtained results, it can be concluded that, unlike the case of the dead load moment variation, the time-dependent deformations of concrete and tendons as well as the construction sequence must also be considered in order to determine the tendon moment variation with time.

3. Determination of tendon moments

3.1. A proposed relation for tendon moment

Construction of a multi-span continuous bridge commences at one end and proceeds continuously to the other end. Therefore, changes in the structural system are repeated whenever a newly constructed span is tied to a preceding span. In advance, the sequential installation of the longitudinal tendons following the construction of each span cause the moment variations in the preceding spans, as shown in Fig. 6. To precisely calculate the final time-dependent moments in a bridge constructed by a MSS (movable scaffolding system), Trost and Wolff [18] proposed a relation on the basis of the combination of elastic moments $\sum M_{S,i}$ occurring after scaffolding at each

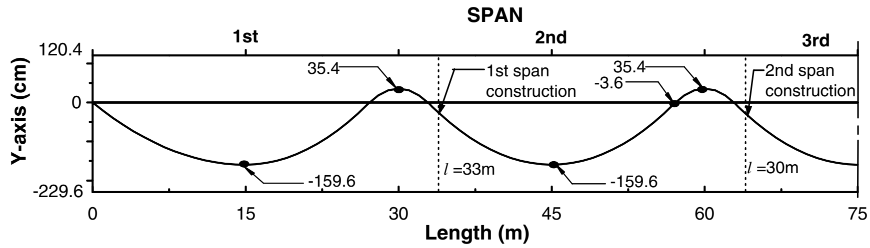


Fig. 5. Tendon profile of the example structure.

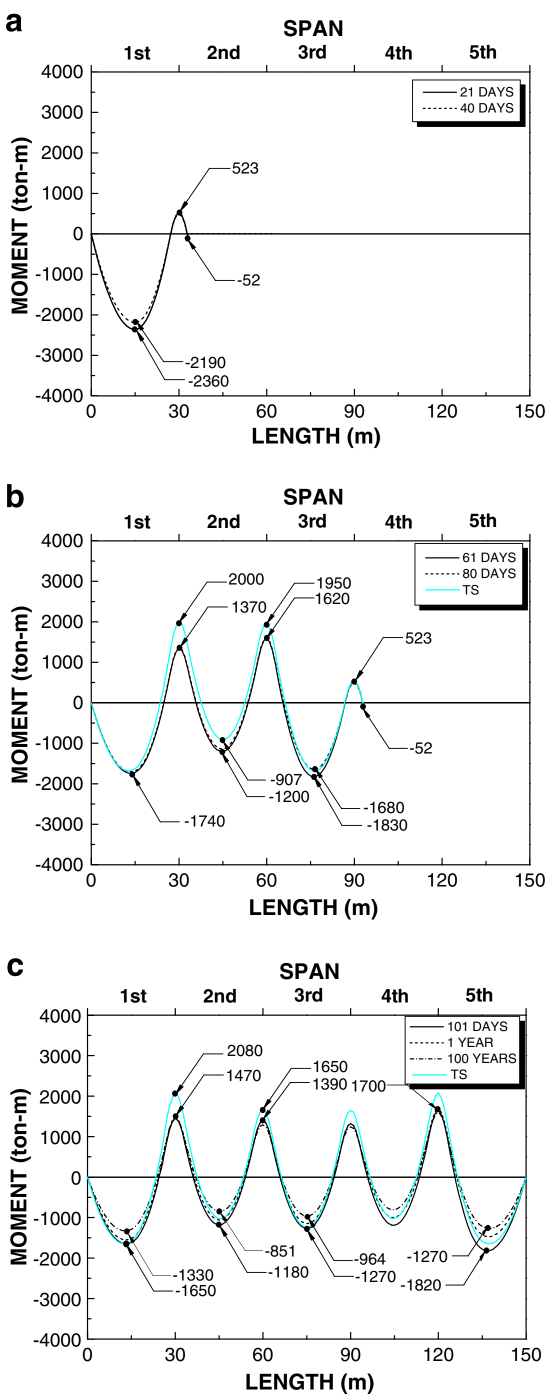


Fig. 6. Tendon moment distribution: (a) after construction of the first span, (b) after construction of the third span and (c) after completion of the bridge.

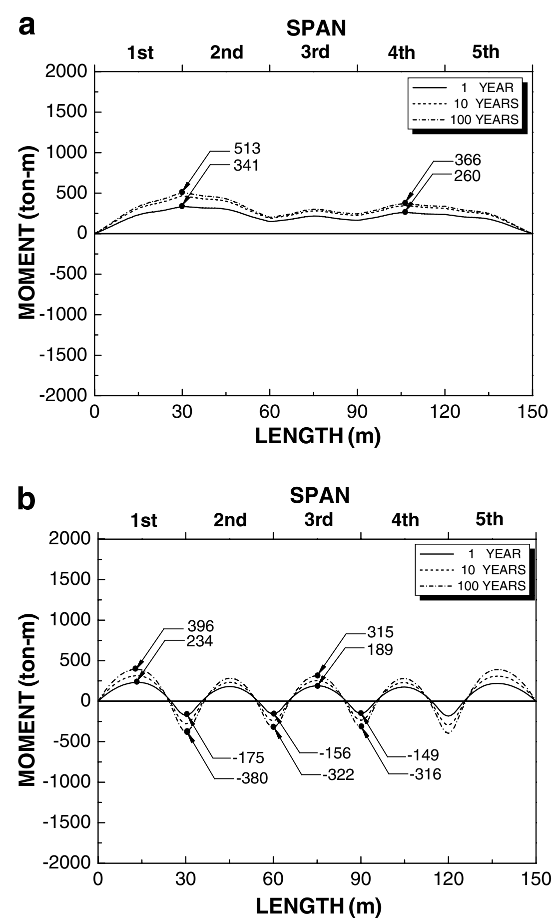


Fig. 7. Time-dependent moment variation: (a) creep moment distribution and (b) moment losses by relaxation.

construction step (see Fig. 8), and the moment obtained by assuming that the entire structure is constructed at the same point in time (M_{E}; corresponding to TS in Fig. 6)

$$M_{\mathrm{T}} = \sum M_{\mathrm{S},i} + \left(M_{\mathrm{E}} - \sum M_{\mathrm{S},i}\right)\frac{\phi_t}{1+\rho\phi_t} \tag{2}$$

where ϕ_t and ρ represent the creep factor and corresponding relaxation factor, respectively.

This relation has been broadly used in practice owing to its simplicity. It is particularly efficient for bridges constructed by ILM (Incremental Launching Method) or MSS (Movable Scaffolding System), i.e., in span-by-span constructed bridges. Nevertheless, there are still limitations

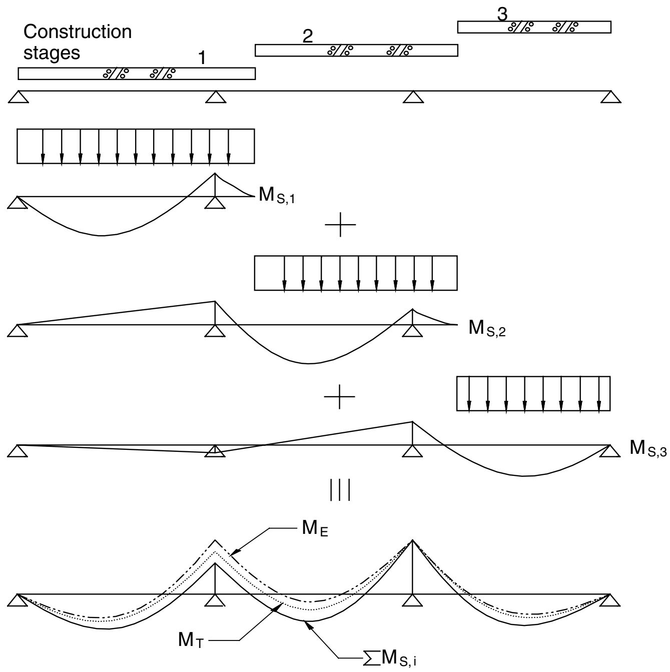


Fig. 8. Combination of $M_{S,i}$.

related to direct applications of Eq. (2) to determine the tendon moments, as this equation cannot take into account the time-dependent moment redistributions according to the construction sequence and the stress relaxation of tendons.

To solve this problem and to accurately simulate the time-dependent tendon moment variation, an improved moment relation is proposed in this paper on the basis of the relaxation phenomenon and construction simulation for MSS. If two simple beams of equal age and of equal span L, carrying a uniformly distributed load w, as time $t = t_0$ day are connected at time $t = t_1$ day and they behave as a continuous beam of two spans in the subsequent duration of time (see Fig. 9(a)), the bending moment at the interior support can be determined from the compatibility condition for the rotation with time at point A in Fig. 9(a). As the well-known derivation procedure can be found elsewhere [6,17], more details are not given in this paper; the moment variation at the interior support can be predicted by

$$M_A(t) = M_A(0) \cdot \frac{\phi(t,t_0) - \phi(t_1,t_0)}{1 + \chi\phi(t,t_1)} \tag{3}$$

where $M_A(0)$ is the moment developed in the elastic structure, indicating that all of the spans are constructed simultaneously at the reference time $t = 0$ day; ϕ is the creep factor; and χ is the aging coefficient. In particular, this equation indicates that the moment $M_A(t)$, induced as a consequence of creep, is proportional to the moment $M_A(0)$ which would develop in an elastic structure.

Given that the time-dependent behavior of a two-span continuous beam effectively describes the internal moment variation in bridges constructed by a movable scaffolding system, with the basic form of Eq. (2) suggested by Trost and Wolff [18] considering the construction sequence while calculating the internal moments at an arbitrary time t, the following relation is introduced in this paper:

$$M_T = \sum M_{S,i} \cdot R(t) + \left(M_E - \sum M_{S,i}\right) \cdot R(t) \cdot f(\phi_t) \tag{4}$$

where $f(\phi_t) = (\phi(t,t_0) - \phi(t_1,t_0))/(1 + \chi\phi(t,t_1))$, and $R(t)$ is the stress relaxation in the tendon and can be determined by $R(t) = f_s/f_{si} = 1 - \log t/10 \cdot (f_{si}/f_y - 0.55)$ introduced by Magura et al. [16], where $f_{si}/f_y \geqslant 0.55$; f_s is the stress at time t, f_{si} is the initial stress immediately after stressing, f_y is the 0.1% offset yield stress, and t is the time in hours after stressing. In the case of low-relaxation tendons, a value of 45 is used instead of 10 in the denominator of the equation $R(t)$. χ is the concrete aging coefficient which accounts for the effect of aging on the ultimate value of

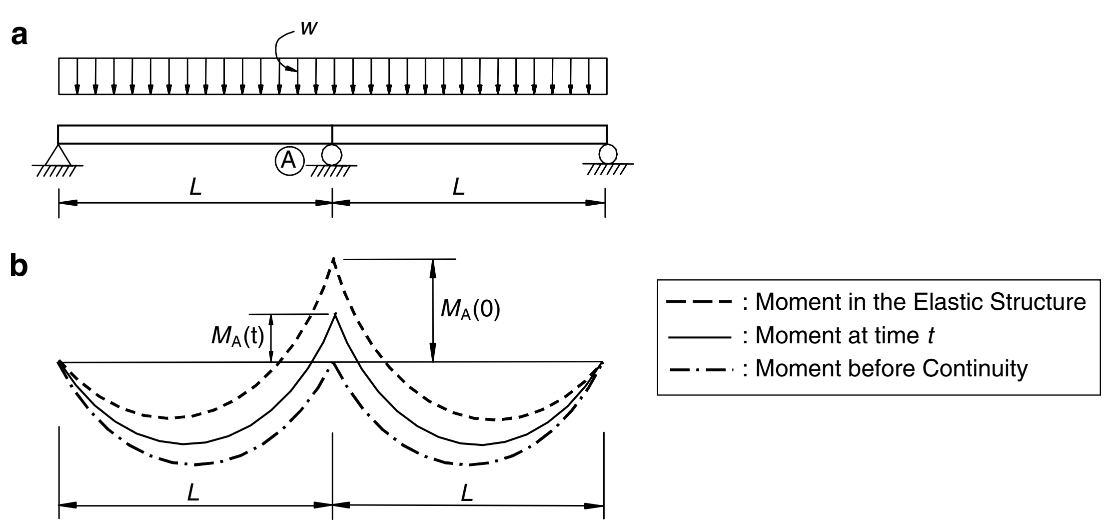


Fig. 9. Moment variation according to the continuity: (a) continuity of two simple beams and (b) moment distribution with time.

creep for stress increments or decrements occurring gradually after the application of the original load. It was found in previous studies [4,6] that an average value of $\chi = 0.82$ can be used for most practical problems where the creep coefficient lies between 1.5 and 3.0. An approximate value of $\chi = 0.82$ is adopted in this paper. In advance, the additional short-term loss caused by friction between the tendon and the duct during jacking can also be considered by determining the initial prestressing force according to an equation adopted in the ACI code [2]; its contribution will be implemented while calculating M_E and $\sum M_{S,i}$ in Eq. (4).

Comparing this equation (Eq. (4)) with Eq. (2), the following differences can be found: (1) since the tendons accompany the moment decrease due to the stress relaxation, even in a structure without any change in the structural system, as well as the moment variation according to changes in the structural system, all of the moment components described in Eq. (4) must include the stress relaxation of the tendon. Based on this aspect, the combination of elastic moments by the longitudinal tendons ($\sum M_{S,i}$) as well as the moment difference caused by the changes in the structural system ($M_E - \sum M_{S,i}$) need to be revised by $\sum M_{S,i} \cdot R(t)$ and $(M_E - \sum M_{S,i}) \cdot R(t)$, respectively; and (2) the term $\phi_t/(1 + \rho\phi_t)$ in Eq. (2) also needs to be revised by $f(\phi_t) = (\phi(t, t_0) - \phi(t_1, t_0))/(1 + \chi\phi(t, t_1))$ to effectively simulate the moment variation in a bridge constructed by MSS (see Eq. (3)).

3.2. Application of the proposal relation

To verify the effectiveness of the introduced relation, the internal tendon moment variations in the example structure after construction, which were obtained through rigorous time-dependent analyses, are compared with those by the introduced relation. The effect of creep in the rigorous numerical model was studied in accordance with the first-order algorithm based on the expansion of a degenerate kernel of the compliance function [11–15], and the stress relaxation was taken into account with the equation introduced by Magura et al. [16]. Fig. 10 representing the obtained results at $t = 1$ year, $t = 10$ years, and $t = 100$ years after the completion of construction, shows that the relation of Eq. (2) proposed by Trost and Wolff gives slightly conservative positive and negative moments, although they are still acceptable in the preliminary design stage. These differences appear to be caused by insufficient consideration of the moment redistribution according to the changes in the construction sequence of the MSS (movable scaffolding system) as well as by a rough implementation of the stress relaxation of the tendons. In particular, the relation proposed by Trost and Wolff (Eq. (2)) shows an increase of the tendon moment from 2000 ton-m at 1 year to 2020 ton-m at 10 years at the first interior support. This result appears to have been caused by the considering the creep deformation of the structure only without an additional implementation for the relaxation of the tendon. Conversely, the relation introduced in Eq. (4) very effectively simulates the internal moment variation over time, regardless of the construction sequence, and gives slightly larger positive and negative moments than those obtained by the rigorous analysis along the spans. Hence, the use of Eq. (4) in determining the internal tendon moments will lead to more reasonable preliminary designs of bridges constructed by a movable scaffolding system.

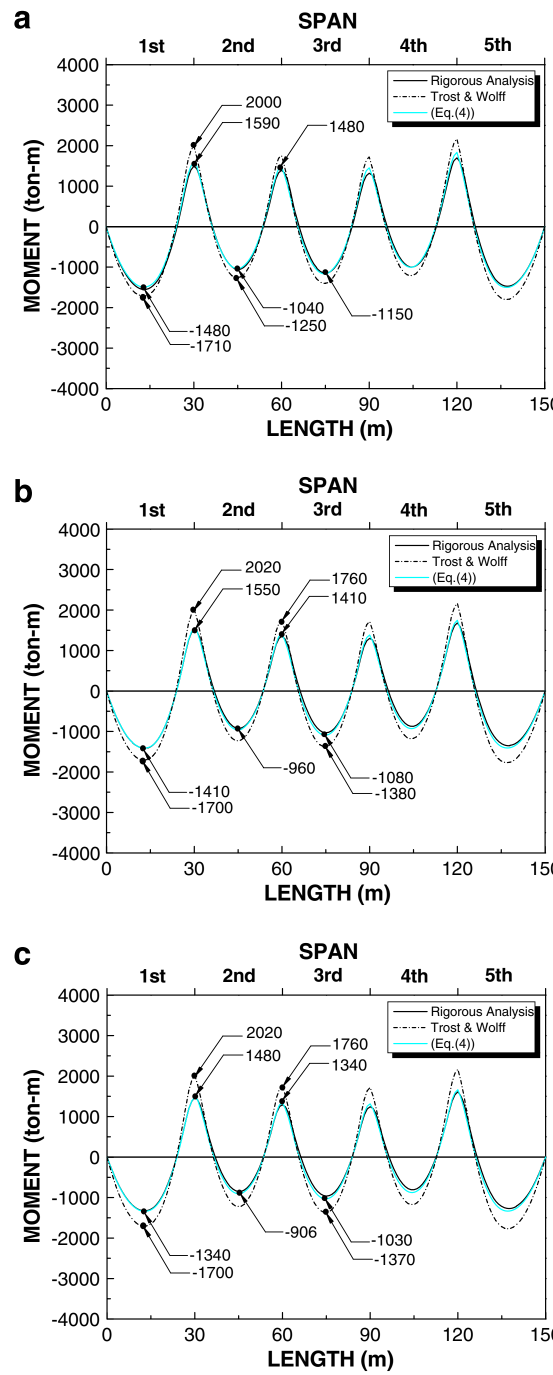


Fig. 10. Tendon moment variations after construction (a) $t = 1$ year, (b) $t = 10$ years and (c) $t = 100$ years.

Fig. 11 shows two tendon moment envelope curves obtained by a rigorous analysis considering the time-

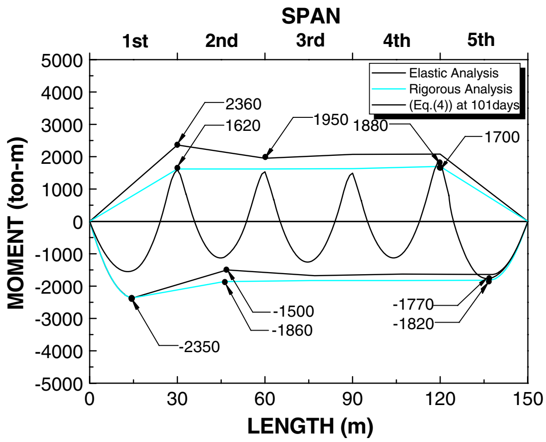


Fig. 11. Tendon moment envelope curves.

dependent deformations of concrete in addition to the stress relaxation of tendons as well as the construction sequence given in Fig. 1 and by an elastic analysis considering the construction sequence only. From the obtained results, the following can be inferred: (1) the bridge experiences the maximum negative tendon moment at the first mid-span after construction of the first span (see Fig. 6(a)), and this moment value is determined as a boundary value for the first mid-span. As the bridge maintains a statically determinate state at this construction step, no moment variation due to the time-dependent behaviors of concrete and tendons appears, and the same boundary values at both envelope curves are produced; (2) the negative moments at each mid-span after the first span represent slightly reduced but uniform values in a bridge constructed by a MSS, as these values are always obtained at the last span post-tensioned at each construction step; (3) the maximum positive moments obtained at each interior support can also be explained by the same reasoning; (4) when the results using Eq. (4) and the rigorous analysis are compared, Eq. (4) proposed in this paper gives a slightly smaller value at the last mid-span for the negative moment and very similar boundary values along the span for the positive moments; and (5) the tendon moment envelope can be constructed with Eq. (4). The positive moment envelope curve is obtained by directly connecting the two boundary values at the first and last interior supports, and the negative moment develop curve can also be determined if the boundary value for the first mid-span is taken from the elastic analysis and if the negative moment value at the last span, obtained by Eq. (4), is used as the boundary value for the other mid-spans.

4. Determination of design moments

To verify the effectiveness of the relation introduced in this paper, the internal moment variations by the dead load and prestressing tendons obtained through rigorous time-dependent analyses [7–9,11,15] are compared with those obtained by the superposition of Eq. (4), and the elastic dead load moment. The five-span continuous bridge in Fig. 1 is taken as the example structure. All of the material properties used in the numerical analyses are identical to those given in Tables 1 and 2 in this paper. Fig. 12 representing the obtained results at $t = 1$ year, $t = 10$ years, and $t = 100$ years after the completion of construction, shows that the superposition of two moments effectively simulates the internal moment variation with time.

The moment envelope curve in Fig. 13, determined from a rigorous analysis considering the construction sequence and the time-dependent behaviors of materials, shows that the proposed method, suggesting the determination of

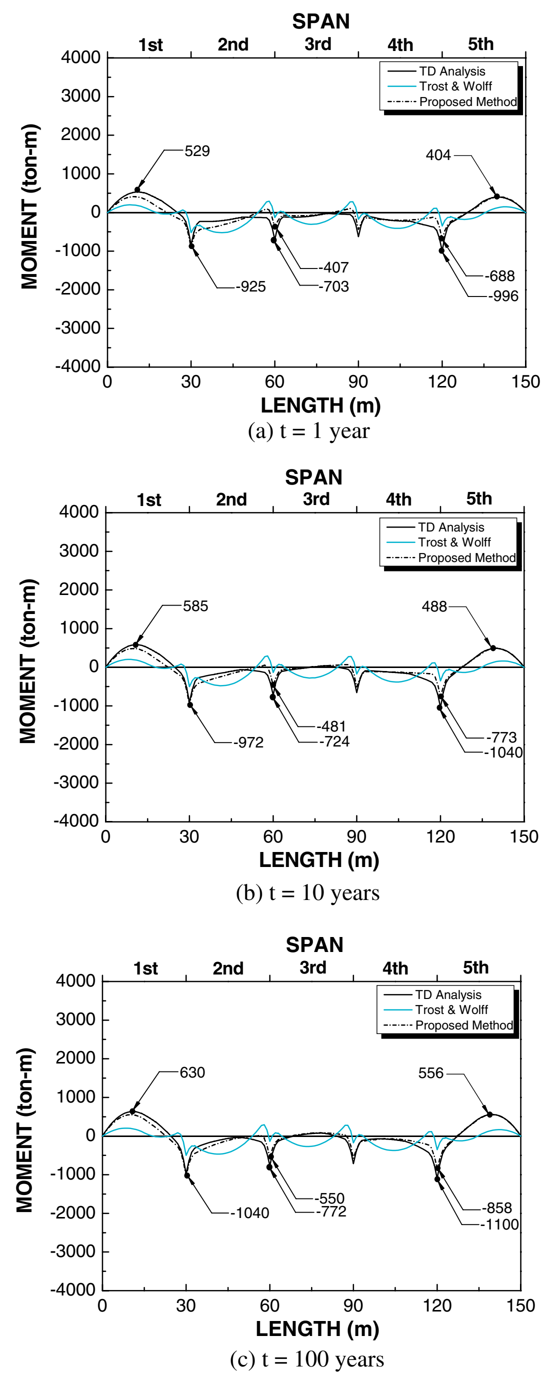


Fig. 12. Total moment variations after construction.

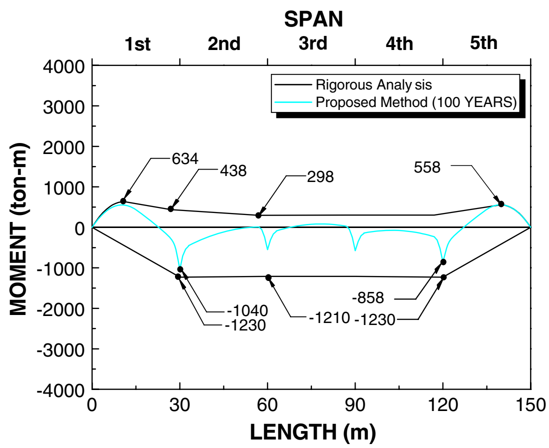


Fig. 13. Total moment envelope curve for example structure.

design moments by the superposition of Eq. (4) for the tendon moment and the elastic moment considering the construction sequence for the dead load moment, effectively represents the boundary values for the maximum and minimum moments used as the reference values in determining the section dimensions in the preliminary design stage.

Therefore, the moment envelope curve can also be constructed with the moment distribution by the proposed method through a similar procedure to that noted with regard to the tendon moment envelope. The positive moment envelope curve can be determined by directly connecting the two boundary values at the first and last mid-spans, and the negative moment at the first interior support can be used as the boundary values for all the interior supports, even though it varies by approximately 13% from the value obtained through the rigorous analysis. This difference does not have a great influence, as the obtained envelope serves as the starting value for the determination of the initial sections of a bridge.

5. Conclusions

A simple but effective relation that can simulate the internal tendon moment variation due to the creep deformation of concrete, relaxation of tendons, and changes in the structural system during construction is proposed; as well, a new method to determine the design moments is introduced in this paper. The design moments for a dead load at any construction step can be determined on the basis of an elastic analysis considering the construction sequence only. The design moments after construction can also be determined from the elastic moment for the total structure without considering any effect. When the longitudinal tendons, which may affect the internal moment redistribution during construction, need to be considered in calculating the internal moments and the corresponding normal stresses at an arbitrary section, Eq. (4) can be suitable employed.

In advance, the moment envelope curves for the dead load, longitudinal tendons, and the superposition of both loads also show that the design moments by the proposed method can effectively be used in determining an initial section assumed for the analysis of a bridge in the preliminary design stage.

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