Structural Effects of Partially Earth-anchored Cable System on Medium-span Cable-stayed Bridges

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Abstract

The aim of this study is to examine the structural effects of the partially earth-anchored cable system on cable-stayed bridges with medium main span length (between 150 and 500 m). It is assumed that the system, originally introduced as a means of reducing excessive axial force in the girder of long-span cable-stayed bridges, can be applied to medium-span cable-stayed bridges. By simulating two types of three-span cable-stayed bridges, one with the self-anchored cable system and the other with the partially earth-anchored cable system, advantages and disadvantages of the partially earth-anchored cable system are estimated. The system enhances structural behaviors for the axial force in the girder, the bending moment in the pylon, and the uplifting force at the bearing. Also, partially earth-anchored cable stayed bridges with the various numbers of earth-anchored cables are analyzed by a parametric study. The major considerations in determining the optimal proportion of earth-anchored cables is recommended.

Keywords: Partially earth-anchored cable system, Cable-stayed bridge, Medium main span, Self-anchored cable system, Number of earth-anchored cable

1. Introduction

Cable-stayed bridges have been recognized as the most economical solution for bridges of 150 to 500 m main span length. Nowadays, cable-stayed bridges having a main span length of over 500 m are also considered to be a suitable type, and indeed, are widely constructed around the world with the help of the development of high-strength materials and advanced technology (Gimsing, 1997; Virlogeux, 1999). In fact, cable-stayed bridges with a main span length of over 1,000 m are now under construction. Since the Öresund bridge with a main span length of 182 m, recognized as the first modern cable-stayed bridge, was constructed in Sweden in 1995 (Walther, 1999), the Normandie bridge, having a main span length of 856 m, and the Tatar bridge with a main span length of 890 m, have come into service (Ito, 1998; Livesey and Larose, 1996; Virlogeux, 1999). And in Hong Kong, the Stonecutter bridge, of 1018 m in main span length, currently is under construction (Tapley et al., 2006) as is the Sutong bridge of 1088 m in China (Feng, 2006). Given these examples, it is predicted that the demand for the even longer-span cable-stayed bridges will arise and increase.

As span length increases, the axial compressive force acting on the girder by way of the horizontal components of the inclined cable forces increases. The bridge girder around a pylon is subjected to serious compressive axial force. If it receives excessive compressive force, the stiffness of the girder is reduced and the critical load decreases (Wang, 1999). Thereby, buckling occurs, and thus higher-strength material or a larger section is required. Also, the potential for dynamic instability due to wind load increases with span length. As a countermeasure for excessive compressive force, Gimsing (1997) suggested a partially earth-anchored cable system. Müllner (1992) suggested a bi-stayed system introducing prestress into the mid-span girders to remove the tensile forces of a partially earth-anchored cable system. Otsuka et al. (1990) studied a partially anchored composite cable-stayed bridge with hinges in the main span. Starossek (1996) suggested a spread-pylon cable-stayed bridge, which uses pairs of inclined pylon legs in order to decrease the compressive force in the girders and reduce the pylon height and the cable lengths. Also, Nagai et al. (2004) showed the possibility of a cable-stayed bridge with a main span length of 1,400 m, by incorporating a section of enlarged width. Its stability was verified using both static and dynamic analyses.

Decreasing the highly compressive forces in the girder of cable-stayed bridges is an interesting problem; to that
end, the partially earth-anchored cable system is selected as the subject of the present study. By applying this system, cable-stayed bridges with very long main span lengths of over 1,500 m can be economically constructed with a special erection method for the central part of the main span (Gimsing, 2006). It should be noted that the existing studies on partially earth-anchored cable-stayed bridges have focused on long-span bridges because of making anchor blocks. However, the partially earth-anchored cable system can be applied also to cable-stayed bridges with medium main span lengths, that is, of between 150 and 500 m, constructed using the free cantilever construction method (FCM). In some bridges, the abutments can be alternative of the anchor blocks.

In order to ensure acceptable behavior of a bridge under earthquake and wind loads, what must be considered are the bridge's dynamic characteristics (Wu et al., 2008). From the literature, it is known that less constraint in the bridge axis direction yields longer natural periods of corresponding motion, and thus reduces the dynamic loads (Ito, 1996). Thus, the partially earth-anchored cable system, since it incorporates longitudinal free supports, will reduce responses to dynamic loads such as seismic force and wind force. Although less constraint causes longitudinal movement of the girder, larger bending in the pylon and larger displacement of the girder, this problem can be solved by earth-anchored cables. Therefore it is anticipated that the structural behavior of medium-main-span-length cable-stayed bridges can be enhanced if the partially earth-anchored cable system is used instead of the self-anchored cable system.

In the present study, the structural effects of the partially earth-anchored cable system are investigated by examining the advantages and disadvantages of this system. Also, by means of a parametric study, the static and dynamic behaviors of medium-main-span-length partially earth-anchored cable-stayed bridges with various proportions of earth-anchored cables are examined. Corresponding 3-D finite element models of the partially earth-anchored cable system and the self-anchored cable system are simulated and compared. Through a construction sequence analysis, a static analysis, and a dynamic analysis, the various member forces and displacements of the two model's major structural components are directly compared.

2. Concept of Partially Earth-anchored Cable System

Most cable-stayed bridges are constructed as a self-anchored cable system in which all of the cables are anchored to the pylon and the girder. In this system, the compressive forces generated by the tensile force of inclined cables are all transmitted to the girder. As the span length increases, the number of cables and cable tensile forces increase. So, the compressive forces acting on the girder increase. The compressive forces can be managed with high-strength steel and moderate strengthening in the critical region around the pylons. When presently produced structural steel is taken into account, the maximum main span length of the self-anchored cable-stayed bridge is around 1,500 m (Gimsing, 2006).

Gimsing suggested the partially earth-anchored cable system in order to make cable-stayed bridges an economical solution to the problems that arise with long spans by reducing the axial force. Such a system anchors some cables to the ground outside of the girder and supports the girder by allowing the longitudinal movements at the pylon and the abutment or the anchor pier. In this

![Figure 1. Comparison of anchoring systems' axial force diagrams.](image-url)
system, tensile axial force can be introduced to the girder at the center part of the main span resulting in a reduction in the excessive compressive axial force in the girder around the pylon. Figure 1 compares the axial force distributions of the two anchoring systems (Gimsing, 2006).

If we assume an ideal partially earth-anchored cable-stayed bridge with a fan-type cable arrangement and a uniform load \( q \), the axial force \( dN \) generated by the uniform load in the small interval \( dx \) (Fig. 2) can be expressed as

\[
dN = (x/h)qdx
\]

For the partially earth-anchored cable system, the boundary condition for determining the axial force diagrams is \( N = 0 \) at the ends of the side spans. So, the axial force diagrams can be obtained according to the equation

\[
N(x) = -\int_{s}^{x} dN - \int_{x}^{h} (x/h)qdx - \frac{q}{2h} (L_s^2 - x^2)
\]

where \( x \) is the distance from the pylon. The maximum compressive axial force is obtained at the location of the pylon \( (x=0) \), and the maximum tensile axial force is obtained at the mid-span \( (x=L_m/2) \). If the absolute values of the maximum tensile and compressive axial forces are the same,

\[
L_m = \sqrt{2} (2L_s)
\]

So, theoretically, the main span length of partially earth-anchored cable-stayed bridges \( (L_m) \) can be extended \( \sqrt{2} \) times longer than that of self-anchored cable-stayed bridges \( (2L_s) \). Also, it has been reported that the main span length of partially earth-anchored cable-stayed bridges can be extended 1.18-1.27 times compared with that of self-anchored cable-stayed bridges (Nagai et al., 1997).

The widely used erection method for three-span cable-stayed bridges is FCM. This method is preferred in the self-anchored cable system. And, although a special erection method is required to introduce considerable tensile forces in the mid-span girder of partially earth-anchored cable-stayed bridges, the FCM construction method might also be applicable to these bridges in cases where a relatively modest tensile region is required, which is the case with medium-main-span-length bridges.

3. FE Model of Bridge

3.1. Bridge description

In order to simulate the behavior of cable-stayed bridges with either the self-anchored cable system or the partially earth-anchored cable system, the three-span cable-stayed bridge is considered; its geometry and dimensions are represented in Fig. 3. The only important problem with regard to the partially earth-anchored cable system is to make the large anchorage block in which the cables are earth-anchored. However, in the present study, a considered bridge could be modeled without designing anchorage blocks, because there are abutments at both ends of the bridge. It is assumed that the earth-anchored cables are anchored to the abutments. Thus are the economic problems caused by making the anchor blocks excluded from the focus of this study; the structural characteristics only are considered.

The main span length is 344 m. The girder section is a steel box of 12.55 m width. The pylon configuration is an A-type shape composed of a steel leg and a concrete pier. The cables, each of the PWS type and arranged in a fan-type, have two planes in the transverse direction. There are six cables in the side span \( (7 \text{ mm} \times 151) \) and nine in the main span \( (3 \text{ ea} (7 \text{ mm} \times 73), 4 \text{ ea} (7 \text{ mm} \times 109), \) and \( 2 \text{ ea} (7 \text{ mm} \times 139) \) for each pylon.

With regard to the supporting conditions of the girder, the vertical and the transverse movements are fixed and the longitudinal movement is free at the abutment. At the pylon, the transverse movement is restrained by wind bearings and the vertical movement is restrained. The longitudinal movements of the girder at the pylon are restrained by rubber bearings in the bridge model with the partially earth-anchored cable system, whereas they are restrained by rubber bearings in the bridge model with the self-anchored cable system. However, in FCM construction sequence analysis, the longitudinal movements of the girder at the pylon are a fixed condition necessary to satisfy construction stability before closing the key-segment for both bridge
3.2. Bridge models

In the case of the bridge model with the self-anchored cable system, all of the cables are anchored to the girder. In the bridge model with the partially earth-anchored cable system, some of the cables are anchored to the abutments. The following four models are considered (Fig. 4): Model M-SE-1, representing the bridge model with the self-anchored cable system; Models M-EA-1, M-EA-2, and M-EA-3, representing the partially earth-anchored cable-stayed bridge model with one, two, and three pairs of earth-anchored cables at the abutments, respectively.

Analysis of cable-stayed bridges is much more complicated than that of conventional bridges, because of the nonlinear structural behaviors due to cable sag, the compression effect in the pylon and the girder, and the large deflections (Karoumi, 1999; Seif and Dilger, 1990; Wang et al., 2004). In the present study, the RM, which is a well-known 3-D finite element program for cable-stayed bridges, is adopted to properly reflect the complicated behaviors of cable-stayed bridges (Pircher, 2004; Janjic et al., 2003). The girder and the pylon are modeled as frame elements, and the stay cables as cable elements. The program can effectively consider a P-delta effect, a cable

<table>
<thead>
<tr>
<th>Member</th>
<th>Location</th>
<th>$A$ (m$^2$)</th>
<th>$I_y$ (m$^4$)</th>
<th>$I_z$ (m$^4$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Girder</td>
<td>General part</td>
<td>0.4965-0.5072</td>
<td>6.912-7.334</td>
<td>0.5912-0.5939</td>
</tr>
<tr>
<td></td>
<td>Support part</td>
<td>0.8021-0.8315</td>
<td>11.41-15.19</td>
<td>0.9999-1.231</td>
</tr>
<tr>
<td>Pylon</td>
<td>Leg</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>United Part</td>
<td>0.5939-1.015</td>
<td>0.7112-4.937</td>
<td>0.5797-1.120</td>
</tr>
<tr>
<td></td>
<td>Separate Part</td>
<td>0.2901-0.4172</td>
<td>0.1913-0.2799</td>
<td>0.2884-0.4169</td>
</tr>
<tr>
<td></td>
<td>Pier</td>
<td>39.88-118.7</td>
<td>564-4783</td>
<td>130.1-288.2</td>
</tr>
<tr>
<td>Cable</td>
<td></td>
<td>-</td>
<td>A=0.002809-0.005811 m$^2$</td>
<td></td>
</tr>
</tbody>
</table>
sagging effect, and a detailed-construction sequence analysis.
Since it is important and difficult to determine the optimal tensioning forces of cables, a number of approaches have been followed (Chen et al., 2000; Janjic et al., 2003; Negrão and Simões, 1997; Wang et al., 1993). Among these approaches, the unit load method (Janjic et al., 2003) is applied in the present study, because it can take into account the actual construction sequences, whereas the other approaches are based on the configuration of the final structure (Lee et al., 2008). Fig. 5 illustrates the configuration of the finite element model.

3.3. Load
3.3.1. Load for construction sequence analysis
A self-weight, an additional dead load, and a construction working load are considered in the construction sequence analysis. The self-weight is calculated using the given material list in the drawings to simulate the exact weights, as follows:

\[ W = \alpha A \gamma_s \]

where \( \alpha \) is the coefficient required to reflect a connection, an anchorage and a diaphragm, among others (girder=1.29, pylon leg (steel)=1.43, pylon pier (concrete)=1.0, cable=1.08); \( A \) is the section area, \( \gamma_s \) is the weight density (steel=77.0 kN/m\(^3\), concrete=24.5 kN/m\(^3\)).

The additional concrete dead load, which is cast in the interior of the side span girders, is 62.39 kN/m after side span construction and the same after the closure of the key-segment. To consider the effect of pavement, a traffic barrier and a railing, a light, a spoiler, and a utility, 35.69 kN/m (girders with spoiler) or 32.79 kN/m (girders without spoiler) is added. During the construction, the effects of a derrick crane (installation, movement, lifting, and removal) and of a construction working live load (10 kN/m) are also considered.

3.3.2. Vehicle load and seismic load
The vehicle load according to the Korean standard vehicle class (MOCT, 2005) is applied to the bridge in its completed state. Also, the response spectrum for seismic analysis, shown in Fig. 6, is applied according to the Korean standard.

3.3.3. Wind load
In order to perform the spectral analysis for wind buffeting loads, some information such as wind climate at the bridge site and aerodynamic forces on bridge section should be assumed. The detail information applied in this study is given in reference (Won et al., 2008). The peak
response is obtained combining mean wind results with RMS buffeting results using the corresponding peak factors for each model.

4. Results and Comparison

The initial analysis considering the construction sequence is performed on the four models. In order to find and compare the optimal cable tensioning forces for the four models, a standard showing similar bending moment diagrams of the girder at the main span and zero displacement at the top of the pylon after completion of construction, is considered. Here, the major member forces of the considered cable-stayed bridges are examined. To find the maximum value, the envelope curves for the four bridges are compared by considering the following loads and load combinations (Table 2).

4.1. Girder member forces

4.1.1. Comparison of bending moments

In order to confirm the standards of the four models, the bending moment diagrams of the girder are plotted for completed construction, as shown in Fig. 7(a), where it can be seen that, indeed, the four models have similar bending moments in the girder at the main spans. Also, for all of the four models, the top displacements of the pylon are approximately zero (0.01~0.07 mm).

When the envelope curves are represented, the bending moments in the girder somewhat increase as the number of earth-anchored cables is increased at the side span and center part of the main span (Fig. 7(b)). It is considered that the use of the partially earth-anchored cable system is somewhat unfavorable. However, the application of a system with one or two pairs of earth-anchored cables is acceptable in the case of this sample bridge.

4.1.2. Comparison of girder axial forces

Axial force diagrams of the girder for the completed construction state are investigated to examine the original effects of the partially earth-anchored cable system (Fig. 8(a)). As the number of earth-anchored cables is increased, the reductive effect of the peak compressive force greatly increases. The reduced compressive force is redistributed

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**Table 2. Considered loads and load combinations**

<table>
<thead>
<tr>
<th>Load</th>
<th>Load combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>D - dead load</td>
<td>1.25D + 1.75L</td>
</tr>
<tr>
<td>L - vehicle load</td>
<td>1.25D + 1.4W</td>
</tr>
<tr>
<td>W - wind load</td>
<td>1.25D + 1.35L + 0.4W</td>
</tr>
<tr>
<td>EQ - seismic load</td>
<td>1.25D + 0.25L + 1.0EQ</td>
</tr>
</tbody>
</table>

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**Figure 7. Comparison of girder bending moments.**

A = Model with self-anchored cable system (M-SE-1)
B = Model with one pair of earth-anchored cable (M-EA-1)
C = Model with two pairs of earth-anchored cables (M-EA-2)
D = Model with three pairs of earth-anchored cables (M-EA-3)
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Compared with the compressive forces of the self-anchored cable-stayed bridge, the bridge model with one pair of earth-anchored cables decreases the compressive force by about 17%, the bridge model with two pairs of earth-anchored cables by 35%, and the bridge model with three pairs of earth-anchored cables, by 53%.

In order to examine the load combination results, the envelope curves of the compressive forces in the girder are investigated for the maximum and minimum combinations (Fig. 8(b) and 8(c)). Compared with the self-anchored system, the peak compressive force of the envelope curves is decreased by 19% in the system with one pair of earth-anchored cables, by 37% with two pairs of earth-anchored cables, and by 54% with three pairs of earth-anchored cables. Specially, in the bridge model with three pairs of earth-anchored cables, the generated peak tensile force in the main span girder is larger than the peak compressive force. Thus, it is considered that application of the partially earth-anchored cable system is a very effective means of reducing the girder axial force; however, the number of earth-anchored cables should be carefully selected in consideration of the increased tensile forces in the girder at the center span.

It is important to know when the tensile forces are introduced into the girder of FCM-constructed, partially earth-anchored cable-stayed bridges. The axial forces in the girder during the detailed-construction stage are investigated. Four sub-stages are examined: before closing the key-segment (the cantilever state), after closing the key-segment (the continuous state), after removing the longitudinal restraints between the girder and the pylon, and after applying an additional dead load (completed construction).

Figure 9 shows the variations of the axial force in the girder for the model with two pairs of earth-anchored cables during the detailed-construction stage. When the continuity of the girder is achieved (after closing the key-segment), tensile forces do not occur, even with the partially earth-anchored cable system. However, after the...
longitudinal restraints between the girder and the pylon are removed, the tensile forces are introduced in the mid-span girder.

Because the two pairs of cables are earth-anchored in this model, the tensile force region ranges between the four cables (in-plane) located in the center part of the main span. An additional dead load applied to all of the girders increases the tensile force in the tensile region as well as the compressive force in the compression region. These results show that the effect of the partially earth-anchored cable system is obtained when the longitudinal restraints are removed. In other words, for partially earth-anchored cable-stayed bridges constructed with the classic FCM method, the reducing effect of axial compressive force occurs when the longitudinally free boundary conditions of the partially earth-anchored cable system are achieved.

4.1.3. Girder deflection

The maximum displacements of the main span are compared to check the serviceability by vehicle load (Table 3). The four models show similar maximum displacements, all satisfying the specification for the displacement (L/400 = 0.86 m). So, it is established that cable system employed does not affect the serviceability caused by the displacements.

4.2. Cable forces

The cable forces in the completed construction state for each model are represented in Fig. 10(a). With regard to the cables on the main span, the four bridge models yield similar results, indicating that the cable forces in the main span do not change. Considering the cables on the side span, the forces slightly increased with the partially earth-anchored cable system. Thereby, the cable forces are increased in intensity, the cable near the earth-anchored cable showing the largest tensile force.

The cable forces for the maximum load combinations are plotted in Fig. 10(b). With regard to the cables on the main span, the forces at the center part are somewhat increased with the increment of the number of earth-anchored cables. Considering the cables on the side span, the forces increased, the cables near the earth-anchored cable showing the largest tensile force. These results are clearly shown in Fig. 11, which represents the cable force ratio for envelope curves, with the self-anchored cable system. Therefore, the use of the partially earth-anchored cable system is somewhat disadvantageous with regard to the side span cables. However, the increased cable forces are small, and thus acceptable, in case of the systems with one or two pairs of earth-anchored cables.

4.3. Pylon moments

The changes of bending moment in the pylon are examined to observe the effects of the earth-anchored cables. As the transverse-direction motion to the bridge axis is not affected by adopting the earth-anchored cables, the longitudinal motion to a bridge axis is of interest only with regard to global bridge motions. The maximum longitudinal bending moments in the pylon and moment ratios to the self-anchored cable system are tabulated in Table 4 according to each load and load combination. For completed construction (dead load), the models with the partially earth-anchored cable system show some increase of bending moments; however, they are very small compared with the effects of the other loads, and so can be ignored.

With regard to vehicle load, the systems with the partially earth-anchored cables show bending moment increments. However, considering the seismic load and wind dynamic load, the systems with the partially earth-anchored cables show reduced maximum bending

![Figure 9. Axial force variations of girders during construction stage (M-EA-2, unit: kN).](image_url)
moments as well as decreasing values for seismic load and wind load that are relatively large compared with the increasing values for the vehicle load. It should be noted that the bridge model with the self-anchored cable system adopts rubber bearings to reduce the seismic effect, whereas the models with the partially earth-anchored cable system use general pot bearings. The reducing effect of the peak bending moments in the pylon by dynamic loads is more remarkable in the partially earth-anchored cable-stayed bridge.

In case of the self-anchored cable system, the dominant load combinations are those of wind load and seismic load. In contrast, for the partially earth-anchored cable system, the seismic load combination is the only dominant load combination. Moreover, the peak moments are reduced by about 10%. Therefore, the partially earth-anchored cable system is more effective in decreasing the pylon dimensions. Most notably, this system better enhances the dynamic behavior resulting from the wind load. The number of earth-anchored cables has only a slight effect.

4.4. Uplift force and movement

The uplift force of the bearings located at the abutment or anchor pier is also an important factor in designing cable-stayed bridges. In most cases, this force is incurred, due to the vertical components of the inclined cables near the bearings, and so preventative devices such as tie-
down cables are installed. Accordingly, moderate treatment of the uplift force guarantees structural integrity of bridges.

The maximum uplift forces of the bearings at the abutment are compared among the four models (Table 5).

As the number of earth-anchored cables is increased, the uplift force notably decreases, except for those small uplift forces developed by the seismic load. The model with one pair of earth-anchored cables (M-EA-1) and that with two pairs of earth-anchored cables (M-EA-2), both diminish the envelope values for the uplift force by about 26% and 51%, respectively, compared with the self-anchored cable-stayed bridge model (M-SE-1). Furthermore, in the model with three pairs of earth-anchored cables (M-EA-3), there is little uplift force. It is concluded that the partially earth-anchored cable system offers a significant advantage in preventing or diminishing the uplift force in the bearings.

As the supports of the partially earth-anchored cable system are in the longitudinal free condition, the movement of the girder is affected. The movements at the expansion joints in the four models are investigated, and the results are tabulated in Table 6.

The movements by the dead load and the vehicle load are increased with the number of earth-anchored cables, which may require an increased expansion joint capacity. However, the movements at the expansion joint due to the wind load and the seismic load show the contradictory result, that is, that the movements decrease as the number

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### Table 4. Maximum pylon longitudinal bending moment for each model (unit: kNm)

<table>
<thead>
<tr>
<th>Load type</th>
<th>M-SE-1</th>
<th>M-EA-1</th>
<th>M-EA-2</th>
<th>M-EA-3</th>
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<tr>
<td>Mz Ratio*</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Dead load (D)</td>
<td>443</td>
<td>1446</td>
<td>1314</td>
<td>534</td>
</tr>
<tr>
<td>Vehicle load (L)</td>
<td>19540</td>
<td>25281</td>
<td>252.99</td>
<td>25034</td>
</tr>
<tr>
<td>Wind load (W)</td>
<td>101554</td>
<td>67038</td>
<td>63062</td>
<td>61996</td>
</tr>
<tr>
<td>Seismic load (E)</td>
<td>142323</td>
<td>125033</td>
<td>123801</td>
<td>123000</td>
</tr>
<tr>
<td>1.25D+1.75L</td>
<td>34749</td>
<td>46049</td>
<td>45846</td>
<td>44477</td>
</tr>
<tr>
<td>1.25D+1.4W</td>
<td>142729</td>
<td>95661</td>
<td>89929</td>
<td>87462</td>
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<tr>
<td>1.25D+1.35L+0.4W</td>
<td>67554</td>
<td>62752</td>
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<td>1.25D+0.25L+1.0E</td>
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<td>133161</td>
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<td>133161</td>
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</table>

*Ratio is the moment ratio to self-anchored cable system (M-SE-1).

### Table 5. Uplift forces at abutment bearings for each model (unit: kN/shoe)

<table>
<thead>
<tr>
<th>Load type</th>
<th>M-SE-1</th>
<th>M-EA-1</th>
<th>M-EA-2</th>
<th>M-EA-3</th>
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<td>Uplift force</td>
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<tr>
<td>Ratio*</td>
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<tr>
<td>Dead load (D)</td>
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<td>3192</td>
<td>1731</td>
<td>305</td>
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<tr>
<td>Vehicle load (L)</td>
<td>3080</td>
<td>2438</td>
<td>1070</td>
<td>820</td>
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<tr>
<td>Wind load (W)</td>
<td>1505</td>
<td>809</td>
<td>810</td>
<td>648</td>
</tr>
<tr>
<td>Seismic load (E)</td>
<td>462</td>
<td>89929</td>
<td>1.75</td>
<td>68.2</td>
</tr>
<tr>
<td>1.25D+1.75L</td>
<td>11164</td>
<td>82.57</td>
<td>7428</td>
<td>2649</td>
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<tr>
<td>1.25D+1.4W</td>
<td>7881</td>
<td>82.57</td>
<td>5428</td>
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</tr>
<tr>
<td>1.25D+1.35L+0.4W</td>
<td>10534</td>
<td>7795</td>
<td>510</td>
<td>2459</td>
</tr>
<tr>
<td>1.25D+0.25L+1.0E</td>
<td>7006</td>
<td>5409</td>
<td>3440</td>
<td>1353</td>
</tr>
<tr>
<td>Envelope</td>
<td>11164</td>
<td>82.57</td>
<td>5428</td>
<td>2649</td>
</tr>
</tbody>
</table>

*Ratio is the uplift force ratio to self-anchored cable system (M-SE-1).
Table 7. Comparison of self-anchored system with partially earth-anchored system

<table>
<thead>
<tr>
<th>Structural Item</th>
<th>Self-anchored cable system</th>
<th>Partially earth-anchored system</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bending moments</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Girder Axial forces</td>
<td>◎</td>
<td>△</td>
</tr>
<tr>
<td>Vertical deflections</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td>Cable forces at main span</td>
<td>△</td>
<td>△</td>
</tr>
<tr>
<td>Cable forces at side span</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Pylon bending moments</td>
<td>○</td>
<td>○</td>
</tr>
<tr>
<td>Uplift forces at bearings</td>
<td>◎</td>
<td>△</td>
</tr>
<tr>
<td>Movements at expansion joints</td>
<td>△</td>
<td>△</td>
</tr>
</tbody>
</table>

Symbols: ○ -relatively good system, ◎ -very good system, △ -similar effect system

of earth-anchored cables is increased. If the load combination results for service limit state are taken into account, it is considered a change from the self-anchored cable system to the partially earth-anchored cable system cannot cause any significant problem at the expansion joint. In fact, in the model with two pairs of earth-anchored cables (M-EA-2), the envelope value of the movements is smaller than that of the model with the self-anchored cable system (M-SE-1).

4.5. Advantages and disadvantages

In the previous section, the various member forces of the considered cable-stayed bridges were examined. The comparison results are summarized in Table 7. Comparing the two systems, the self-anchored cable system shows good structural behaviors for bending moments in the girder and cable forces at the side span. The bridge model with the partially earth-anchored cable system shows enhanced structural behaviors for axial forces in the girder, bending moments in the pylon, and uplifting forces at the bearings. The two system exhibit similar results for the vertical deflection of the girder, the cable forces at the main span, and the movements at the expansion joints.

4.6. Comments for the number of earth-anchored cables

The structural behaviors of partially earth-anchored cable-stayed bridges with various numbers of earth-anchored cables were examined in previous chapters. As the number of earth-anchored cables is increased, the reducing effect on the peak compressive force in the girder, as well as the uplifting force in the bearing, greatly increases, but the tensile force in the main span girder also increases. Earth-anchored cables significantly reduce the pylon bending moment developed by the dynamic load, but the number of earth-anchored cables only has a slight effect in reducing the pylon bending moments. The partially earth-anchored cable-stayed bridge model shows increased cable forces at the side span and the largest of these forces is in the cable nearest the earth-anchored cable. Therefore, in determining the number of anchored cables, the allowable level of the tensile force and the compressive force in the girder and the maximum cable force are major considerable factors.

5. Conclusions

As described and explained in this paper, the structural effects of the partially earth-anchored cable system were studied by comparison with the self-anchored cable system. Through a construction sequence analysis, a vehicle load analysis, as well as wind dynamic load and seismic load analyses, the various member forces for each anchoring system were examined. The bridge model with the partially earth-anchored cable system, compared with that with the self-anchored cable system, shows enhanced structural behaviors for the axial force in the girder, the longitudinal bending moment in the pylon, and the uplifting force at the abutment bearings. The bridge model with the self-anchored cable system, meanwhile, exhibits better behaviors for the bending moment in the girder and the cable forces at the side span. For the vertical deflection of the girder, the cable forces at the main span, and movements at the expansion joints, the two models exhibit similar results. It is considered, in accordance with all of the results, that the structural behaviors are enhanced when the partially earth-anchored cable system is applied to cable-stayed bridges with a medium main span length of between 150 and 500 m.

The parametric study for the partially earth-anchored cable-stayed bridges with various numbers of earth-anchored cables shows the important design factors to engineers. In determining the number of anchored cables, it is recommended that the allowable stress level of both the tensile force and the compressive force in the girder and the maximum cable force are major considerable factors.

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References

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