Wind and Structures, Vol. 11, No. 6 (2008) 441-453
DOI: http://dx.doi.org/10.12989/was.2008.11.6.441

Effects of partially earth-anchored cable system on dynamic wind response of cable-stayed bridges

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(Received August 4, 2008, Accepted September 20, 2008)

Abstract. In this study, a partially earth-anchored cable system is studied in order to reduce the dynamic wind response of cable-stayed bridges. The employment of earth-anchored cables changes the dynamic characteristics of cable-stayed bridges under wind loads. In order to estimate the changes in the member forces, the spectral analysis for wind buffeting loads are performed and the peak responses are evaluated using 3-D finite element models of the three-span cable-stayed bridges with the partially earth-anchored cable system and with the self-anchored cable system, respectively. Comparing the results for the two different models, it is found that the earth-anchored cables affect longitudinal and vertical modes of the bridge. The changes of the natural frequencies for the longitudinal modes remarkably decrease the peak bending moment in the pylon and the movements at the expansion joints. The small changes of the natural frequencies for the vertical modes slightly increase bending moments and deflections in the girder. The original effects of the partially earth-anchored cable system are also shown under wind loads; the decrement of girder axial forces and bearing uplifting forces, and the increment of cable forces in the earth-anchored cables.

Keywords: partially earth-anchored cable system; wind response; cable-stayed bridge; dynamic characteristics; buffeting load.

1. Introduction

Since, in most cable-stayed bridges, the horizontal components of the inclined cable forces are transmitted to the girder, the axial compressive force is introduced into the girder. As span length increases, the axial compressive force acting on the girder is increased. Excessive compressive force will cause buckling in the girder (Wang 1999), and thus requires higher strength materials. Some researchers make an effort to reduce the axial compressive force in the girder (Gimsing 1997, Otsuka, *et al*. 1990, Starossek 1996). Also, there is a recent study to combine the cable-stayed bridge and the suspension bridge (Zhang 2007).

Gimsing (1997) suggested a partially earth-anchored cable system in order to reduce the excessive compressive force in the girder. In this system, the peak compressive axial force in the girder around the pylon can be decreased by adopting longitudinal free support conditions of the girder and anchoring some cables to the ground outside of the girder, whereas the tensile force is introduced into

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the mid-span girder. Even though the partially earth-anchored cable system is studied for long span cable-stayed bridges with a special erection method for the central part of the girder in the main span, the partially earth-anchored cable system can be applied to cable-stayed bridges with medium main span lengths, that is, of between 150 and 500 m, constructed using general erection method.

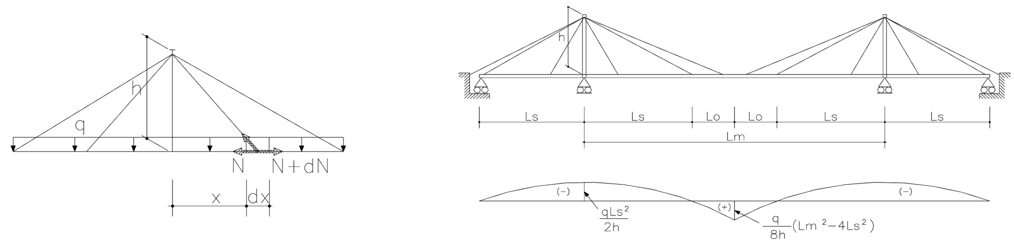
When the partially earth-anchored cable-system is considered as the means of reducing the axial force in the girder for long span cable-stayed bridges, the additional anchor blocks or bigger anchor piers are needed. Thus, the construction cost of the substructure will be more expensive. In addition, it is noted that the work of earth-anchoring is more complex and expensive than that of self-anchoring, and the soil condition affects anchoring condition. Even though the use of higher strength materials will be an adequate solution in case that the partially earth-anchored cable system is not applicable, it is also noted that the combination of high-strength materials and the partially earth-anchored cable system can be more effective solution for long span cable-stayed bridges.

The use of partially earth-anchored cable system changes the dynamic characteristics of cable-stayed bridges and some variation of major member forces are anticipated. To ensure acceptable behavior of cable-stayed bridges under dynamic load, the dynamic characteristics must be considered (Wu, *et al*. 2008). It is known that less constraint in the bridge axis direction yields longer natural periods of corresponding motion, and thus reduces the effects of the dynamic loads (Ito 1996). Since the partially earth-anchored cable system is in the longitudinal free supporting condition, it is predicted that the responses to dynamic loads such as seismic force and wind force will be reduced. Thus, it is interesting subject to quantitatively examine the effect of the partially earth-anchored cable system on the structural behavior of cable-stayed bridges. First of all, it is needed to examine the wind response of the partially earth-anchored cable-stayed bridge since the design of cable-stayed bridges is mainly dominated by wind loads.

The aim of this study is to estimate the structural effects of the partially earth-anchored cable system on the wind response of cable-stayed bridges by means of a comparison with the self-anchored cable system. In some bridges, the abutments can be alternative of the anchor blocks. By assuming the earth-anchored cables are anchored to abutments, the economic problems caused by making the anchor blocks excluded from the focus of this study. The structural characteristics only are considered. Two bridge models are considered for three-span cable-stayed bridges, one with the partially earth-anchored cable system and the other with the self-anchored cable system. The multimode spectral analyses for wind buffeting loads are performed using 3-D finite element models. The peak responses are estimated by combining the results of mean wind analysis with those of root-mean-square (RMS) buffeting analysis using the corresponding peak factors for each mode. The various member forces of the two models are investigated to estimate the effects of the partially earth-anchored cable system.

2. Partially earth-anchored cable system

Most cable-stayed bridges incorporate a self-anchored cable system. In this system, compressive forces generated by the tensile force of the inclined cables are all transmitted to the girder. The peak compressive force in the girder is occurred around the pylon. As the span length increases, the peak compressive force in the girder increases. The increased compressive forces can be managed with high strength steels and moderate strengthening in the critical region around the pylon (Gimsing 2006). Gimsing recommended the partially earth-anchored cable system as a means of reducing the axial force. In this system, some cables are anchored to the ground outside of the girder, and the girder supporting conditions allow longitudinal movements at the pylon and the abutment or anchor



(a) Load transmission to the girder (b) Axial force diagram

Fig. 1 Axial force diagram of ideal partially earth-anchored cable-stayed bridges

pier. Thus the tensile axial force can be introduced into the girder at the center part of the main span, whereas the excessive compressive axial force in the girder around the pylon is decreased.

If the uniform load (q) is applied to an ideal partially earth-anchored cable-stayed bridge with a fan type, the axial force (dN) generated by uniform load in the small interval (dx) can be expressed as follows (Fig. 1).

$$dN = (x/h)qdx \tag{1}$$

Since the boundary condition for determining the axial force diagrams is $N = 0$ at the ends of the side spans, the axial force diagrams can be obtained as follow equations.

$$N(x) = -\int_x^{Ls} dN = -\int_x^{Ls}(x/h)qdx = -\frac{q}{2h}(Ls^2 - x^2) \tag{2}$$

where x is the distance from the pylon. The axial force diagram is shown in Fig. 1(b).

Theoretically, the main span length of partially earth-anchored cable-stayed bridges (Lm) can be extended $\sqrt{2}$ times longer than that of self-anchored cable stayed bridges ($2Ls$), which is obtained by assuming the absolute value of the maximum tensile and compressive axial force are same.

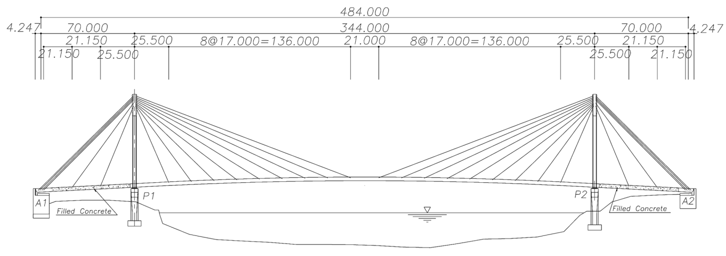
3. Numerical example

A three-span cable-stayed bridge is selected for a sample bridge. Two bridge models are simulated for estimating the dynamic response under wind loads, one with the partially earth-anchored cable system and the other with the self-anchored cable system.

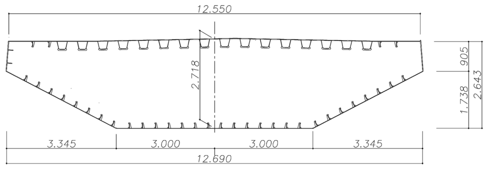
3.1. Bridge description of sample bridge

The following three-span cable-stayed bridge is considered in the present study (Fig. 2). There are abutments at both ends of the bridge. It is assumed that the earth-anchored cables are anchored to the abutments. The main span length is 344 m, and a steel box girder section is used. The cables have two planes in the transverse direction. In one plane, there are six cables in the side span (7 mm × 151) and nine in the main span (from the pylon, 3 ea (7 mm × 73), 4 ea (7 mm × 109), and 2 ea (7 mm × 139)) for each pylon.

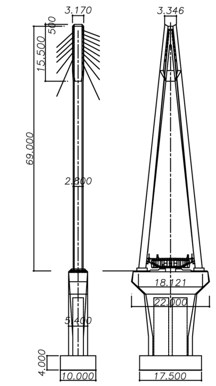
The vertical and the transverse movements of the girder are fixed and the longitudinal movement of the girder is free at the abutment. At the pylon, the transverse movement of the girder is restrained by



(a) Side view



(b) Cross-section of girder



(c) Pylon

Fig. 2 Sample bridge

Table 1 Main properties of sample bridge

Member	Location		A (m^2)	I_y (m^4)	I_z (m^4)
Girder	General part		0.4965 – 0.5072	6.912 – 7.334	0.5912 – 0.5939
	Support part		0.8021 – 0.8315	11.41 – 15.19	0.9999 – 1.231
Pylon	Leg	United Part	0.5939 – 1.015	0.7112 – 4.937	0.5797 – 1.120
		Separate Part	0.2901 – 0.4172	0.1913 – 0.2799	0.2884 – 0.4169
	Pier		39.88 – 118.7	564 – 4783	130.1 – 288.2
Cable	-		A = 0.002809 – 0.005811 m^2		

wind bearings and the vertical movement of the girder is restrained. The longitudinal movements of the girder at the pylon are free 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.

The main sectional properties of the sample bridge are listed in Table 1. In the table, A is a sectional area and I is a moment of inertia of the section. In the girder section, the subscript of y means vertical axis and z is normal to bridge axis. In the pylon section, y is bridge axis direction and z is normal to bridge axis.

3.2. FE model

The bridge is modeled using the 3-D finite element program. Since the cable-stayed bridge shows nonlinear behaviors due to cable sag, the compression effect in the pylon and the girder, and large deflections, any analysis tool employed should properly consider such complicated behaviors. RM software, which is a 3-D finite element program that shows good results in wind buffeting analysis of cable-stayed bridges, is used. The accuracy of buffeting analysis was verified in other large

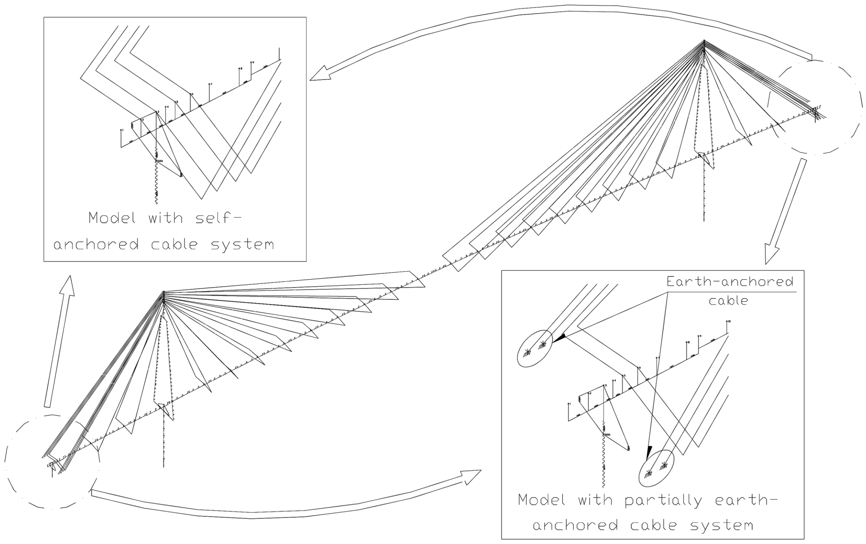


Fig. 3 3-D finite element model

bridge projects (Janjic, *et al*. 2003, Pircher 2004, Janic 2006). The girder and the pylon are modeled as the frame element. The cable is modeled as the cable element. Fig. 3 illustrates the configuration of the FE model. In the model of partially earth-anchored cable-stayed bridges, the number of the earth-anchored cables should be determined. In the present study, the partially earth-anchored cable-stayed system with two pairs of earth-anchored cables at the abutments is considered.

3.3. Wind loads for spectral analysis

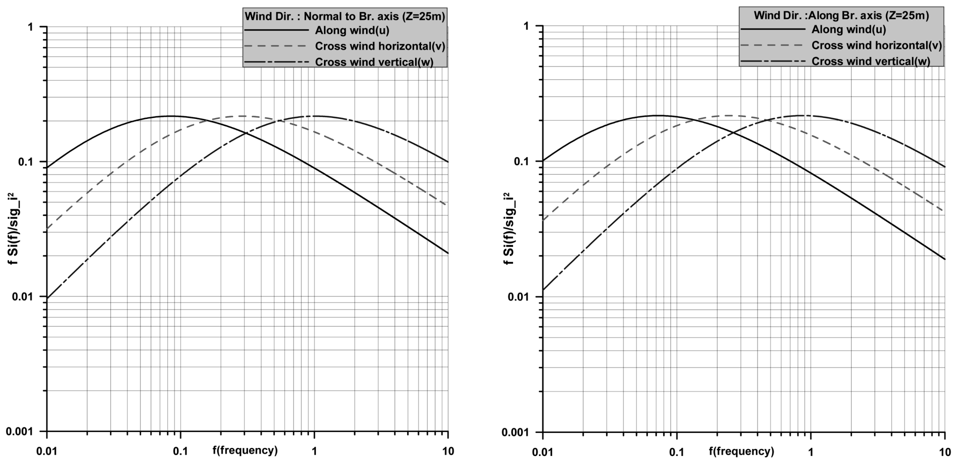
It has become common to express the aerodynamic forces per unit span as the sum of the aeroelastic part (self-excited part) and the external buffeting part (aerodynamic part) (Scanlan 2006). Although the time-domain buffeting analysis is recently developed, the frequency-domain analysis is more attractive for its simplicity and efficiency (Ding, *et al*. 2002). Since multimode buffeting analysis is widely used, which is based on frequency-domain method and takes into account the fully coupled aeroelastic and aerodynamic response of long span bridges under wind excitations (Simiu and Scanlan 1996, Jones and Scanlan 2001), in the present study, the multimode spectral analysis is carried out to simulate the wind response. The first 50 vibration modes are included. The structural damping is assumed to be 0.005 and the aerodynamic admittance function is considered as unity in the present study.

In order to estimate the peak response to the wind load by spectral analysis, information such as the wind climate at the bridge site and the aerodynamic forces on the bridge section should be assumed (Chen 2006). In the present study, a logarithmic variation of the wind speed as function of the level above ground is assumed. The assumed properties of fluctuating velocity are summarized in Table 2. In the Table, V_b is the basis wind speed (36.8 m/s), z (m) is the level above terrain, z_0 (m) is the terrain roughness (0.0075 for wind normal to the bridge axis, 0.05 for wind along the bridge axis), and k_t is the terrain factor (0.17 for wind normal to the bridge axis, 0.19 for wind along the bridge axis).

Representing the spectral density of the fluctuating velocity components, the Kaimal spectrum is assumed, as

Table 2 Properties of fluctuating velocity

Item	Properties
10-min mean wind speed	$V_{10}(z) = V_b \cdot k_t \cdot \ln\left(\frac{z}{z_0}\right)$
Gust wind speed	$V_g(z) = V_{10}(z) \cdot (1 + 3.5 \cdot I_u(_z))$
Turbulence intensity	$I_u(z) = \frac{1}{\ln(z/z_0)}$
Intensity function of the atmospheric turbulence	$I_i = \frac{\sigma_i}{V_{10}(z)}$ $i = u$ (along wind), v(cross wind horizontal), w(cross wind vertical velocity)
Standard values of i'th velocity (σ_i)	$\sigma_u = k_t \cdot V_b,\ \sigma_v = 0.8 \cdot k_t \cdot V_b,\ \sigma_w = 0.6 \cdot k_t \cdot V_b$



(a) Normal to bridge axis (b) Along bridge axis

Fig. 4 Applied wind spectrum example

$$\frac{f \cdot S_i(f)}{\sigma_i^2} = \frac{\dfrac{L_i \cdot f \cdot z}{V_{10}(z)}}{\left[1 + 1.5 \cdot \dfrac{L_i \cdot f \cdot z}{V_{10}(z)}\right]^{5/3}} \tag{3}$$

where $S_i(f)$ is the spectral density of the fluctuating velocity component i, f is the frequency of velocity fluctuation, and L_i is the length scale of turbulence component i ($L_u = 24$, $L_v = 7$, and $L_w = 2$). The example of the Kaimal spectrum at a deck height is shown in Fig. 4.

The coherence of the fluctuating velocity components and the cross-spectral density function of the velocity fluctuations at two points separated by a distance Δ are expressed as

$$\mathrm{Coh}(f,\Delta) = \exp\left(-\frac{2 \cdot c \cdot f \cdot \Delta}{V_{10}(z)}\right) \tag{4}$$

$$S_{ii}(f, \Delta) = S_i(f) \cdot \sqrt{\mathrm{Coh}(f, \Delta)} = S_i(f) \cdot \exp\left(\frac{-c \cdot f \cdot \Delta}{V_{10}(z)}\right) \tag{5}$$

where c is the decay parameter (=8), and Δ is distance between the considered points in a plane perpendicular to the direction of the mean wind.

The aerodynamic coefficients of the pylon, stay cable, and girder are applied as listed in Table 3. In the table, D, L, M are the aerodynamic drag force, lift force, and moment/unit length of girder. $1/2\rho V^2$ is a dynamic head of the wind, B is a girder width, and H is a girder height.

The basic equations and assumptions of the used FE model are represented in the references (Janjic and Pircher 2004, Jinjic 2006).

4. Effects of partially earth-anchored cable system

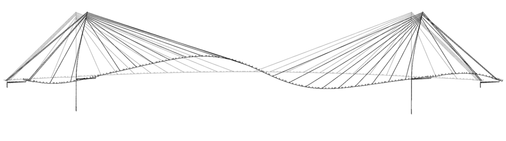
The spectral analysis for wind buffeting loads is performed to the sample bridge. First, the natural frequencies and vibration mode shapes are compared. The member forces of the girder, the cable, and the pylon are investigated for the self anchored cable-stayed bridge and the partially earth-anchored cable-stayed bridge in order to evaluate the effects of the partially earth-anchored cable system.

4.1. Dynamic characteristics

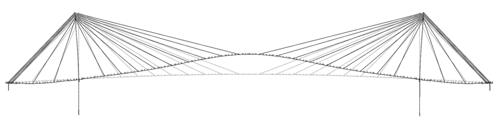
The important natural frequencies and vibration modes are represented for the bridge model with the partially earth-anchored cable system (Fig. 5) and that with the self-anchored cable system (Fig. 6). In

Table 3 Aerodynamic coefficients of pylon, cable, and girder

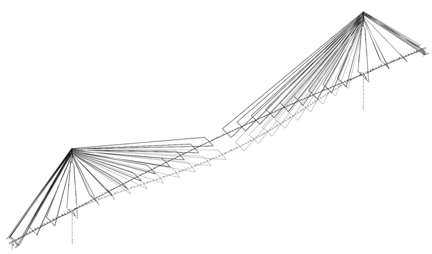
Components		Coefficient
Pylon drag(C_D)		1.8 for longitudinal wind 1.8 for transverse wind − upwind leg 0.9 for transverse wind − downwind leg
Stay cable drag(C_D)		1.0
Girder	Drag	$C_{D,0} = 0.49$, $dC_{D,0}/d\alpha = 0$[Deg^{-1}] (where, $C_D = D/(1/2\rho V^2 H)$)
	Lift	$C_{L,0} = -0.029$, $dC_{L,0}/d\alpha = 0.034167$[Deg^{-1}] (where, $C_L = L/(1/2\rho V^2 B)$)
	Moment	$C_{M,0} = -0.043$, $dC_{M,0}/d\alpha = -0.008$[Deg^{-1}] (where, $C_M = M/(1/2\rho V^2 B^2)$)



(a) 1st longitudinal mode (f=0.363Hz)



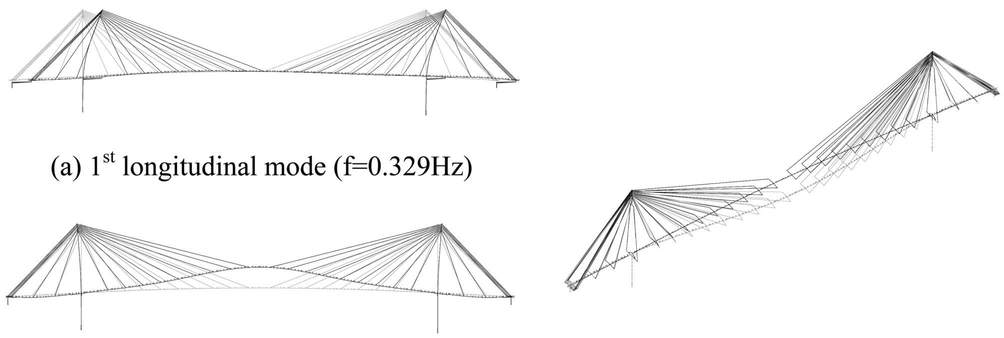
(b) 1st vertical mode (f=0.454Hz)



(c) 1st transverse mode (f=0.347Hz)

Fig. 5 Natural frequencies and modes of partially earth-anchored cable-stayed bridge model the bridge model with the partially earth-anchored cable system, the first vibration mode shape is found in a transverse direction. The second mode shape is a longitudinal direction and third is a vertical direction. In the bridge model with the self-anchored cable system, the first vibration mode is a longitudinal vibration mode and the second is a transverse direction, and third is a vertical direction.

The natural frequencies are compared (Table 4). The natural frequency of the longitudinal mode remarkably changed since the boundary condition is changed in the longitudinal direction. The



(a) 1st longitudinal mode (f=0.329Hz)

(b) 1st vertical mode (f=0.460Hz) (c) 1st transverse mode (f=0.344Hz)

Fig. 6 Natural frequencies and modes of self-anchored cable-stayed bridge model

Table 4 Comparison of natural frequencies

Mode shape	Model	Mode Number				
		1	2	3	4	5
Longitudinal	SE[1)]	0.329				
	EA[2)]	0.363				
	Difference	9.37%				
Vertical	SE	0.460	0.673	1.036	1.276	1.366
	EA	0.454	0.713	1.040	1.285	1.372
	Difference	-1.32%	5.61%	0.38%	0.70%	0.44%
Transverse	SE	0.344	0.960	1.827	2.715	3.002
	EA	0.347	0.964	1.830	2.714	3.007
	Difference	0.86%	0.41%	0.16%	-0.04%	0.17%
Torsional	SE	2.468				
	EA	2.473				
	Difference	0.20%				
Pylon Longitudinal	SE	2.274	2.849	3.415	4.084	5.640
	EA	2.268	2.854	3.400	4.086	5.594
	Difference	-0.26%	0.18%	-0.44%	0.05%	-0.82%
Pylon Transverse	SE	1.497	3.364	3.764	5.075	5.521
	EA	1.497	3.377	3.760	5.073	5.525
	Difference	0.00%	0.38%	-0.11%	-0.04%	0.07%

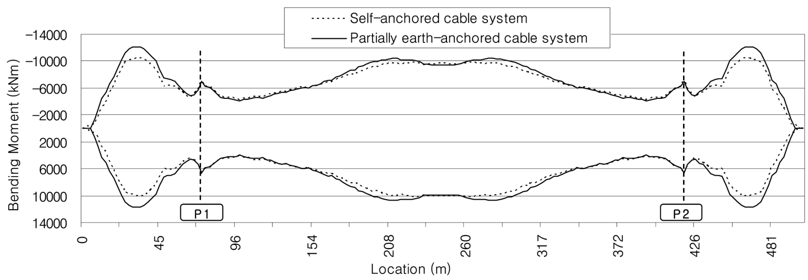
1) Bridge model with self-anchored cable system

2) Bridge model with partially earth-anchored cable system

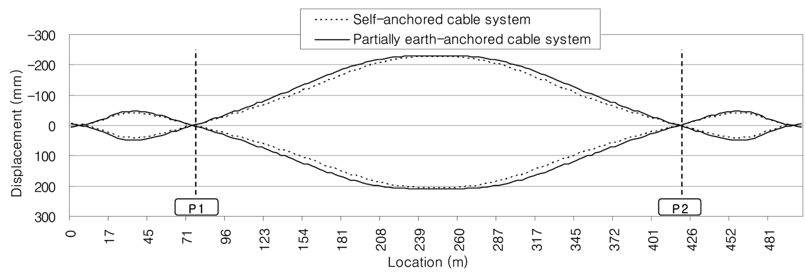
longitudinal movements are only restrained by the earth-anchored cables in the bridge model with the partially earth-anchored cable system. With regard to the vertical mode, the natural frequencies are somewhat changed since the earth-anchored cables control the vertical motion and increase the geometrical stiffness by reducing the axial forces in the bridge girder. For the transverse and torsional modes of the girder and the pylon vibration mode, the natural frequencies are similar. It is considered that the earth-anchored cables only affect the longitudinal and vertical modes of the bridge.

4.2. Comparison of wind responses in girders

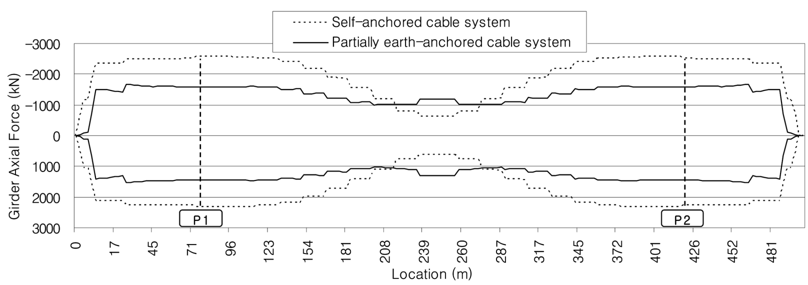
The changes of girder forces and displacements are investigated. Fig. 7 represents the results of



(a) Bending moment of girders (kNm)

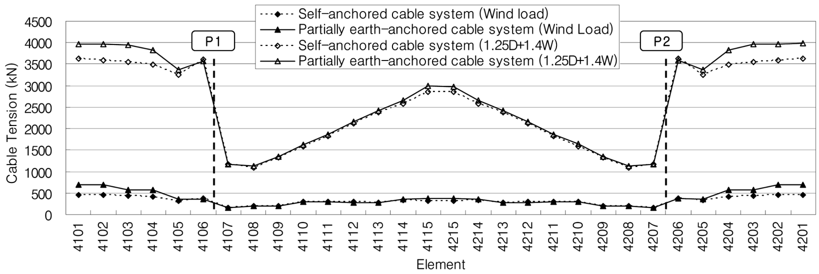


(b) Displacements of girders (mm)

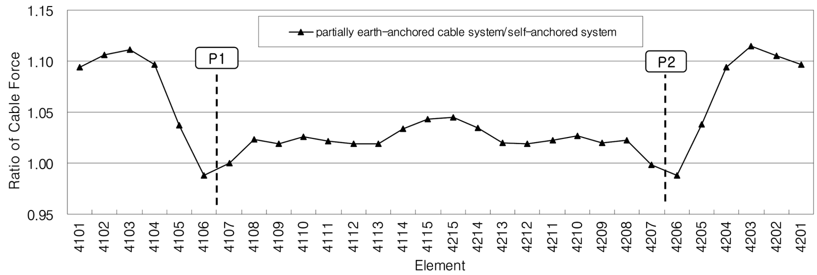


(c) Axial forces of girders (kN)

Fig. 7 Comparison of girder member forces and displacements



(a) Force by wind load and load combination (1.25D(dead load) + 1.4W(wind load)) (kN)



(b) Force ratio by load combination

Fig. 8 Comparison of cable forces

comparison between two models. With regard to bending moments and deflections of the girder, in the bridge model with the partially earth-anchored cable system, the bending moments and the deflections slightly increased (Fig. 7(a) and (b)). These result from the small increment of the natural frequencies of the vertical modes. From Fig. 4 and Table 4, it is found that the natural frequencies of the partially earth-anchored cable-stayed bridges are more close to the peak vertical components of wind spectra. Axial force distributions of the girder are also examined (Fig. 7(c)). The figures show the original effects of the partially earth-anchored cable system. The axial forces are decreased in the most of the girder parts except the center of the main span. Therefore, it is thought that the bridge with the partially earth-anchored cable system is more effective to reduce girder responses on wind loads.

4.3. Variation of cable forces

The cable forces by wind loads are examined for two models. Fig. 8 represents the comparison of the cable forces. Also, the cable forces of a load combination with dead loads are investigated since the cable forces developed by wind loads are small. Fig. 8(a) shows the changes of cable forces and Fig. 8(b) shows the ratio of cable forces to the self-anchored cable-stayed bridges. With regard to the cables on the main span, two models show the similar cable forces. Considering the cables on the side span, in the bridge model with the partially earth-anchored cable system, the cable forces increased and some cables show the increment of 10% since the earth-anchored cables strongly resist the deformation of the pylons. Therefore, the use of the partially earth-anchored cable system is somewhat disadvantageous in the side span cables.

4.4. Reduction of pylon moments

The changes of bending moment in the pylon are examined to observe the effect of the earth-anchored cables on wind loads. As the transverse direction motion to the bridge axis is not affected by the earth-anchored cables (Table 4), the longitudinal motion is of interest only with regard to global bridge motions. The maximum longitudinal bending moments in the bottom of the pylon and moment ratios to the self-anchored cable system are tabulated in Table 5. For the dead load, the model with the partially earth-anchored cable system shows some increment of moments. However, these increased values are very small compared to those of wind loads, thus can be ignored. The reducing effect of the peak pylon bending moments under wind loads is more remarkable in the partially earth-anchored cable-stayed bridge because of the change of natural frequencies of the longitudinal and vertical vibration modes due to the earth-anchored cables. The peak moments of a load combination is reduced by about 37% in the model with the partially earth-anchored cable system. Therefore, the partially earth-anchored cable system offers an effective advantage in the reduction of the maximum moment in the pylon. Thus, the longitudinal dimension of the pylon can be reduced since the pylon design mainly is dominated by dynamic load such as wind loads.

4.5. Other effects

The uplift forces of the bearings on the abutments or anchor piers are an important factor in designing cable-stayed bridges. Due to the vertical components of the inclined cables near the bearings, the uplift forces are incurred, and so the preventing devices such as tie-down cables should be installed. Accordingly, moderate treatment of the uplift forces guarantees structural safety of the bridges. The peak uplift forces are compared (Table 6). The model with the partially earth-anchored cables diminishes the peak uplift force by about 29%. Since the number of cables anchored to the girder adjacent to the abutment is reduced, the vertical components of cable forces which affect the uplift force are decreased. It is thought that the partially earth-anchored cable system offers a good advantage in preventing or diminishing the uplift forces in the bearings.

Since the supports of the partially earth-anchored cable system are in the longitudinal free condition, the system affects the movements of the girders. The maximum movements at the

Table 5 Maximum pylon longitudinal bending moment for each model (unit: kNm)

Load Type	Self-anchored CSB model (*a*)	Partially earth-anchored CSB model (*b*)	Ratio(*b*/*a*)
Dead load (D)	443	1,314	2.966
Wind load (W)	101,554	63,062	0.621
1.25D + 1.4W	142,729	89,929	0.630

Table 6 Comparison of uplift forces and movements

	Self-anchored CSB model (*a*)	Partially earth-anchored CSB model (*b*)	Ratio(*b*/*a*)
Uplift forces at abutment bearing (kN/shoe)	1,505	1,070	0.711
Movements at expansion joints (mm)	145.6	103.8	0.713

expansion joint are investigated, and the maximum results are tabulated in Table 6. The movement due to the wind loads is remarkably decreased in the partially earth-anchored cable system by the shifts of the natural frequencies for the longitudinal modes. Thus, the system is effective for reducing the movements by wind loads even though it has the free support conditions in the direction of a bridge axis.

5. Conclusions

As described and explained in this paper, the effects of a partially earth-anchored cable system on the dynamic behaviors of the cable-stayed bridges were studied through the spectral analysis for the wind buffeting loads. From the results, it is found that the earth-anchored cables affect the longitudinal and vertical modes of the bridge. In the bridge model with the partially earth-anchored cable system, bending moments and deflections in the girder slightly increased by the small changes of the natural frequencies for the vertical modes, which make the natural frequencies to move close to the peak vertical components of wind spectra. However, the shifts of the natural frequencies for the longitudinal modes remarkably decrease the peak bending moment in the pylon. The peak value is reduced by about 37% in the sample bridge. Therefore, the partially earth-anchored cable system offers an effective advantage in the reduction of the maximum moment in the pylon, thus reducing the dimensions of the pylon. Also, the movements at the expansion joints are reduced by the change of the natural frequencies for the longitudinal vibration modes. The axial forces in the girders and the uplifting forces in the bearing on the abutments are decreased under the wind loads, and these are the original effects of the partially earth-anchored cable system. The disadvantage in the employment of the partially earth-anchored cable system is the increased tensile forces in the side span cables.

Acknowledgement

This work has been supported by Yonsei University, Center for Future Infrastructure System, a Brain Korea 21 program, Korea.

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