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Effect of Pylon Shapes on Seismic Response of a Long-Span Steel Box-Girder Cable-Stayed Bridge

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Abstract

In recent decades, the demand for complex and economical engineering structures with great aesthetics has been on the rise and the cable stayed bridges also take their share of this interest. Besides many advantages cable-stayed bridges are quite flexible, hence susceptible mainly to dynamic actions such as impact loads, wind effects and seismic excitations. In this context, this study focused on the effect of A and H shape reinforced concrete pylons on the seismic behavior of a long span steel triple box-girder cable-stayed bridge that was presumed to be located in an earthquake-prone region in Turkey. The 3D models of the bridge were constructed using SAP2000 software and the time history analysis have been carried out considering cable sag, large displacement effects. The seismic responses of the bridges are compared in terms of axial force on cables, deflections on the pylons and the deck.

1. Introduction

Cable-stayed bridges have become more popular especially in seismic prone areas over the past decades. This popularity is directly related to the massive improvement in technological know-how in terms of material quality, powerful computation tools and construction strategies. The use of cable-stayed bridges dates back to 16th century. But, after the Second World War, cable-stayed bridges gained more prominence with the first modern steel cable-stayed bridge of 183 m main span constructed in Sweden in 1955. Evolution of this form of bridge over the years has been tremendous. Today, the main span length of cable-stayed bridges exceeded 1000 meters. The Russky Bridge in Vladivosstok has the longest main span length (1104m) in the world. Cable-stayed bridges are generally compared with suspension bridges. Though very similar, cable-stayed bridges have a major distinctive difference from suspension bridges. The stay-cables in the cable-stayed bridges travel directly from the tower to the anchorage point on the deck girder at an angle less than 90^0 (between 20°-60°) creating a fan-like or harp-like cable pattern. Meanwhile, for the suspension bridge cables, they generally run vertically on the deck attached to a main cable placed horizontally from tower to tower through the bridge structure. The main advantages of the cable-stayed form over suspension bridges can be listed as the increased rigidity, lower deformation and rapid construction. On the other hand, cables are the primary load-bearing members in cable-stayed bridges and extra strain induced on the cables deserves special care during the design stage especially under dynamic excitations such as wind load and seismic actions.

Several studies were conducted on the seismic behavior of cable-stayed bridges over the last decades [1-26]. These studies revealed that the flexibility and susceptibility of the bridge is dependent on many factors such as the main span of the bridge, the cable pattern, the support conditions at the piers, the damping type, material

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properties, soil-structure interaction, etc. The shape of the pylons are assumed to be an aesthetic feature as the effects of pylon shapes are not so prominent for structural design of short span cable-stayed bridges. However, it is imperative to use certain pylon shapes in case of long span cable-stayed bridges in order to satisfy structural safety [27-30]. Accordingly, this study examined the effect of two different pylon shapes of a long span cable-stayed bridge that is postulated to span the Izmit Bay in Kocaeli, Turkey.

Figure 1. Location of the Cable-Stayed Bridge (Google Earth ©2020 Google, ©2020 Basarsoft, Image©2020 Maxar Technologies)

2. Materials and Method

2.1. Description of the Bridge

Cable-stayed bridges are generally made of three major parts which are cables, pylon and deck. The proposed cable-stayed bridge was assumed to be spanning the Izmit Bay and linking the Derince District to Gölcük District (Figure 1). The location of the bridge was decided considering the shorter route between both districts. It should be noted that this region is densely occupied by industrial facilities along the banks of İzmit Bay on both sides. Hence, the bridge will serve to decongest the traffic and create ease of interaction between these two districts. Also, along this route the deepest point below sea level is approximately 50 m with an average gradient of 4% from shore to deepest point which creates a quiet shallow and short route linking both districts [31]. Nevertheless, Izmit Bay, which is situated along an urbanized and industrialized coastal line of the Marmara Sea, lies on the Northern Anatolian fault (Strike Slip fault) which suffered a major rupture lastly on August 17th, 1999 with a registered magnitude of Mw = 7.4

The overall span length of the bridge is 2000 m consisting of a main span of 1200 m, side spans of 400 m and two pylons with 78 stay cables on each side of a pylon. Intermediary piers are placed 80 m away from each other at the side span. The heights of the piers vary due to the inclination of the bridge deck (Figure 2). The deck of the bridge is inclined along the longitudinal direction with a slope of 2.5% to compensate for the sag effect of the cables and the mid-span moment of the deck due to self-weight. In addition, this inclination allows a clear passage for sea vessels such as ships envisaged to go under the structure.

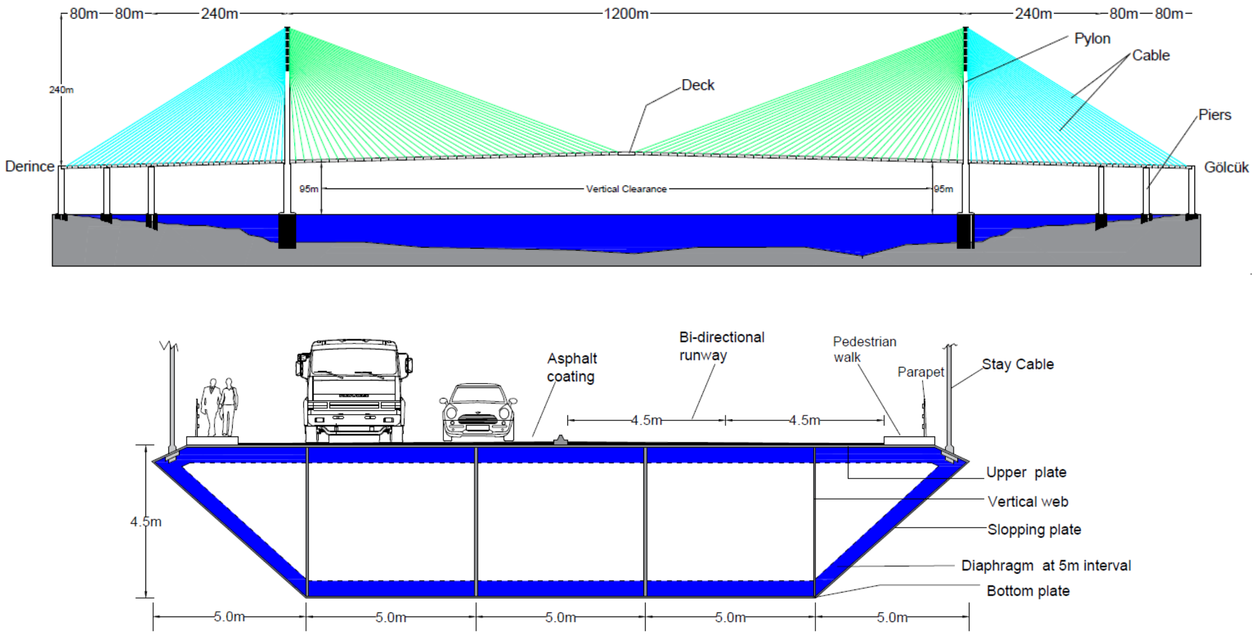

Figure 2. Side view of the bridge and the cross-section details of the bridge deck.

The deck is connected to the pylons by 0.15 m diameter galvanized high tension steel cables spaced at 10 m for side span and 15 m for main span from each other (Figure 2)

The deck of the bridge is a trapezoidal triple box steel girder with a maximum height of 4.50 m as shown in Figure 2. The deck width was decided to be 25 m for two bi-directional lanes with pedestrian walks on both sides. The height to span ratio of the bridge is relatively high compared to the other examples in the literature. The equivalent thickness of upper and lower orthotropic steel plates and the sloping base plates of the deck were assumed to be 20 mm considering the trapezoidal stiffeners. The equivalent thickness of the web is 30 mm including the trapezoidal stiffeners. Transversal steel cross beams were provided to restrict distortional effects in every 5 meters along the deck.

Even though other parameters such as the deck and pylon cross-section, deck-pier connection type, pylon – deck connection type etc. may affect the behavior of the cable-stayed bridge, an illustration of the dynamic response of a long span cable-stayed bridge was predominantly demonstrated through the variation of the pylon shape. The emphasis was laid on the shape of the pylon as the other aspects were assumed to be identical for the sake of accurate comparison.

The commonly used A and H shaped pylons were taken into consideration in the scope of this study (Figure 3). The pylon cross sectional dimensions were determined considering a preliminary design procedure prescribed in the literature [20].

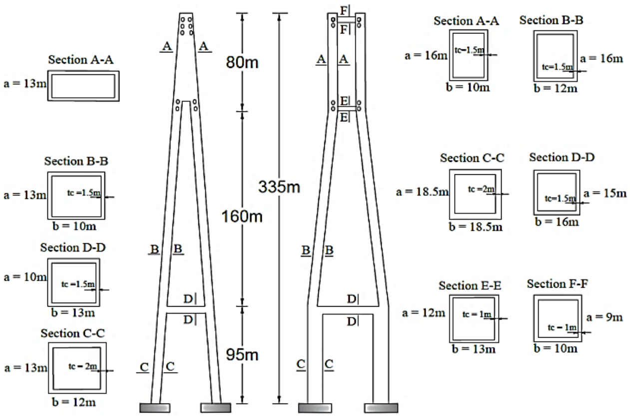

Figure 3. Dimensions of the A and H shape reinforced concrete pylons.

2.2. Material Properties

Self-compacting concrete with compressive strength of 80 MPa was preferred in the design of pylons and piers. The cable strands were galvanized and provide higher tensile strength with respect to regular steel. These strands with a nominal diameter of 15.7 mm, consist of seven helical wires. The characteristic tensile strength of strands is 1860 MPa. Material nonlinearity has not been taken into consideration throughout the analysis; all the components were assumed to behave in a linear-elastic manner.

2.3. Finite Element Model of the Bridge

Structural analysis software SAP2000 [32] was used to create the finite element model of the bridge. Pylons and piers were considered as fixed at the bottom, deck-pylon connection considered as partially fixed with movement predominantly in the horizontal x-direction linked by viscous dampers and elastomeric bearings in order to mimic the actual behavior. The cable element uses an elastic catenary formulation to represent the behavior of a slender member under self-weight. This catenary cable element is highly nonlinear and inherently accounts for P-Δ effect and large displacement. The deck was modelled using shell elements. Frame elements were used to define pylons, struts and transverse cross-beams. 3-D finite element model of cable-stayed bridge with A-shape pylon is shown in Figure 4.

2.4. Dynamic Characteristics of Bridges

The modal behavior of the cable stayed bridges should be evaluated in detail to study seismic behavior of such structures. For this purpose, an initial dead load analysis was performed considering the geometric nonlinearity. Then, pretension was applied to the cables considering the deflected shape under dead load. Finally, Ritz vectors modal analysis was carried out to investigate the dynamic characteristics of the bridge. First six vibration modes and corresponding natural periods for bridges with A and H shape pylons are listed in Table 1 and mode shapes are displayed in Figure 5 for comparison purposes.

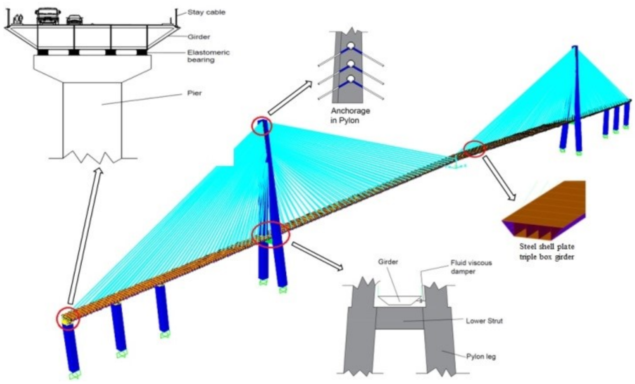

Figure 4. 3-D finite element model of the bridge with A-shape pylon

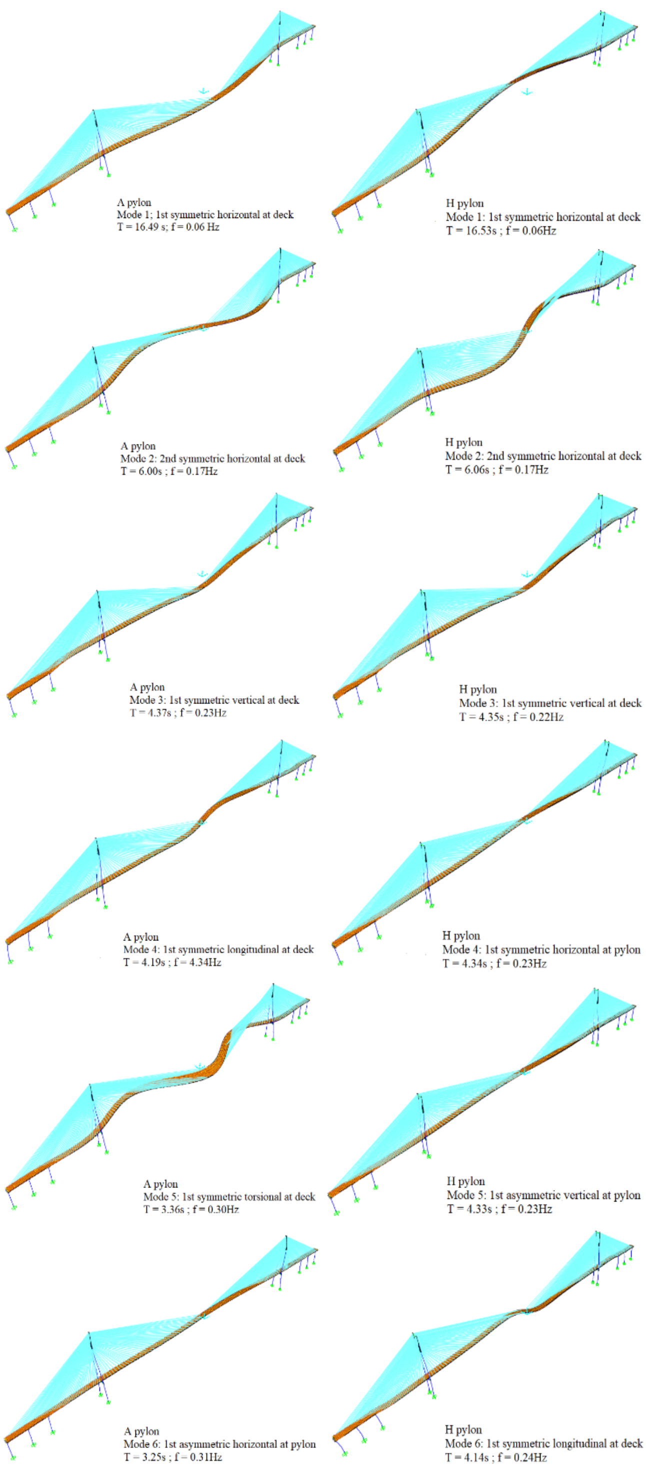

Figure 5. First six fundamental modal shapes of the bridge models

First three fundamental vibration modes are identical for both pylon types and vibration periods are very close to each other. The tower vibration become dominant at 4th fundamental mode for H-shape pylon which is relatively earlier with respect to A-shape pylon. There is a difference in the number of vibration modes to attain a 95% mass participation ratio for two models. This difference can be attributed to the type of pylon shape. The variation of cumulative modal mass participation factor with respect to number of modes is shown in Figure 6.

Table 1. Comparison of natural periods and mode shapes

Mode No	A-Shape Pylon		H-Shape Pylon	
	Period (sec)	Mode Shape	Period (sec)	Mode Shape
1	16.49	1st S-H Deck	16.54	1st S-H Deck
2	6.00	2nd S-H Deck	6.06	2nd S-H Deck
3	4.37	1st S-V Deck	4.35	1st S-V Deck
4	4.19	1st S-L Deck	4.34	1st S-H Pylon
5	3.36	1st S-T Deck	4.33	1st A-H Pylon
6	3.25	1st A-H Pylon	4.14	1st S-L Deck
S: symmetric, A: asymmetric, H: horizontal, V: vertical , L: longitudinal T: torsional				

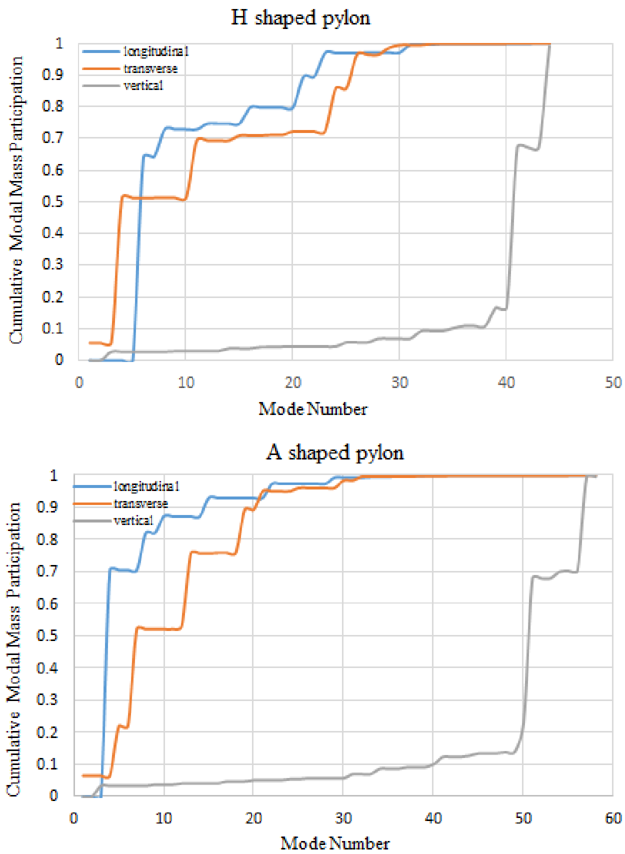

Figure 6. Modal mass participation ratio vs. number of modes in three principal directions for both pylon types

2.5. Time History Analysis of Bridge Models

Time history analysis was carried out to investigate the seismic response of the bridge models with different pylon shapes. Two types of geometric nonlinearity, namely p-delta effects and nonlinearity due to cable sag were considered. Kocaeli Earthquake in 1999 was the major earthquake of the near past in the neighborhood of the bridge location. Therefore, all three components (North-South, East-West and Vertical) of the Kocaeli Earthquake record from the closest station (Yarimca YPT) were used for the time-history analysis. Figure 7 shows the acceleration response spectra of the 1999 Kocaeli Earthquake.

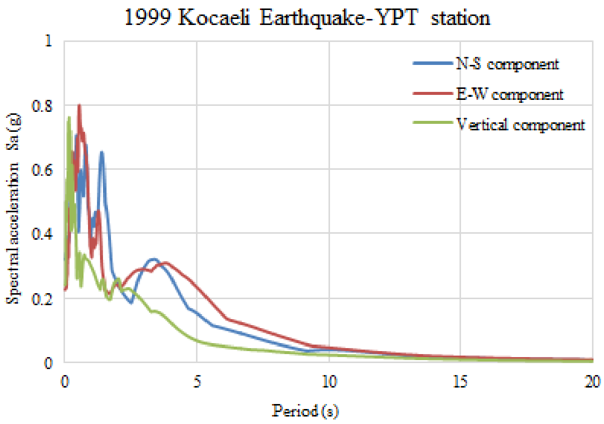

Figure 7. Spectral acceleration of 1999 Kocaeli earthquake in the three orthogonal directions

The direct-integration method was employed in the nonlinear time history analysis due to its capability to perform nonlinear direct-integration time-history analysis. In SAP2000 [32], different numerical solution algorithms are available for performing the nonlinear direct-integration time-history analysis. The "Hilber-Hughes-Taylor alpha" (HHT) method was utilized in this study to conduct the nonlinear time history analysis. The time interval employed for this numerical simulation is 0.01 second. The damping of structure was idealized by Rayleigh damping model. The effective viscous damping of the overall system was assumed to be 2% at period values of 0.11 second and 16.5 second considering the higher modes. Gravity load from the self-weight of the bridge was initially applied prior to time history analysis to simulate the actual behavior.

3. Results and Discussion

The seismic responses of the bridges are compared in terms of axial force on cables, deflections on the pylons and the deck. Figure 8 shows the axial load variation in the heavily loaded cables for different pylon shapes. The maximum axial force was observed for the bridge with H-shape pylon. However, the effect of pylon type on the maximum cable force is not very significant for the current study.

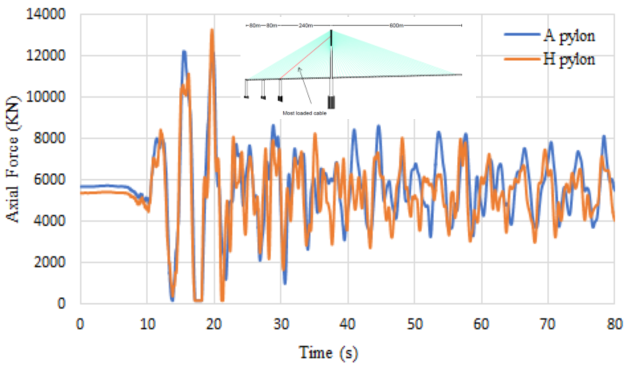

Figure 8. Axial force variation for the critical cable

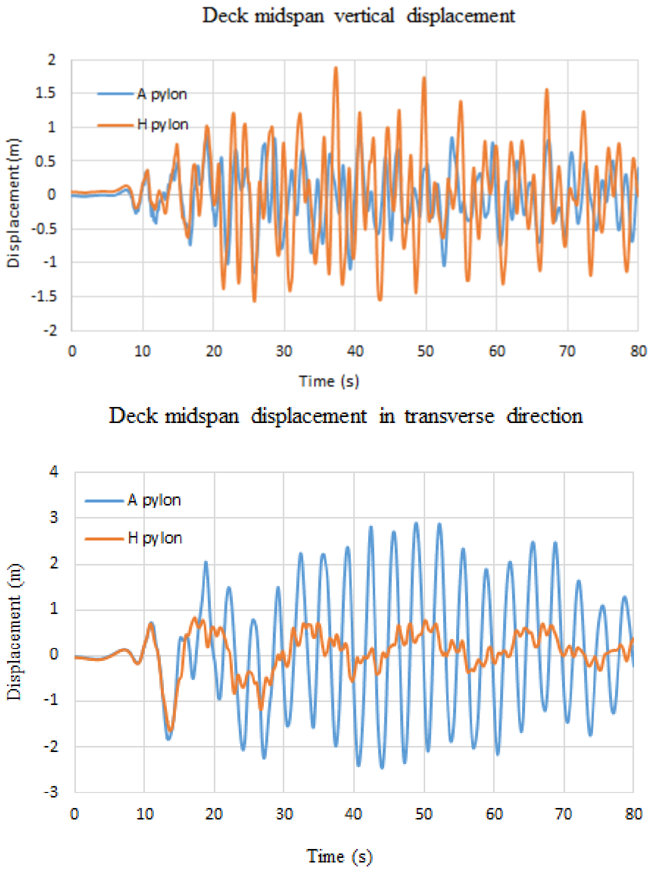

Figure 9. Comparison of Deck Midspan Displacement

The deck midspan displacement in vertical and transverse direction are presented in Figure 9 for two different bridge models. The analysis results indicated that midspan vertical displacement is relatively greater in bridge with H-shape than bridge with A-shape pylon. On the other hand, significant difference was observed in terms of deck midspan deflection response in the transverse direction. The amplitude of transverse midspan displacement is almost equal to 3 meters for the cable-stayed bridge with A-shape pylon.

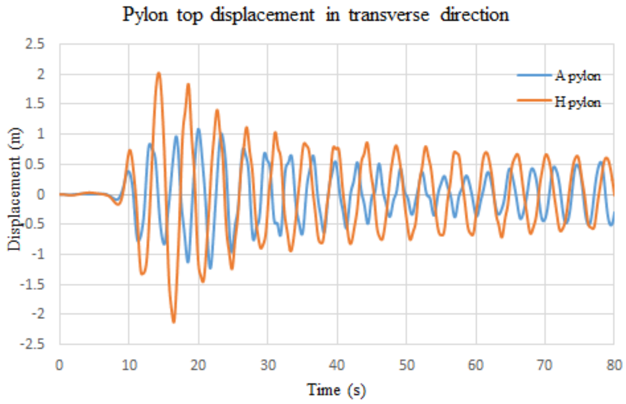

Figure 10. Pylon Top Displacement in Transverse Direction

Figure 10 displays the effect of pylon shape on the pylon top displacement in transverse direction. The analysis results revealed that the maximum transverse displacement of the H-shape pylon top is almost two times greater than that of the A-shape pylon.

4. Conclusions

In this study, the effect of A and H-shape pylons on the seismic behavior of a long span steel triple box-girder cable-stayed bridge that was assumed to be located in an earthquake prone region was investigated. Only geometric nonlinearities were taken into account throughout the analysis and the bridge models were analyzed considering the effect of dead loads, cable pretension forces and seismic excitation. The cross-section dimensions of the reinforced concrete pylons were decided considering a preliminary design procedure prescribed in the literature. The pylon vibration become dominant in the earlier modes for H-shape pylon with respect to A-shape pylon. This behavior possibly led to almost two-fold difference among the maximum pylon top transverse displacements of the two different pylons, namely H-shape pylon experienced greater displacement. On the contrary, the maximum deck midspan transverse displacement was observed in cable-stayed bridge model with A-shape pylon. It should also be emphasized that the pylon shape has almost no significant effect on the axial load variation on the most critical cable for the current study.

Declaration of Ethical Standards

The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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