



Seismic Reliability Analysis of Three-Dimensional Harp Type Cable Stayed Bridge

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Abstract. Cable-stayed bridges are getting popularity because they are economical for longer spans. The cable-stayed bridge is nonlinear and highly indeterminate. So, it is required that the various elements should be modelled properly to represent the actual behaviour of structure as close as possible. In this study, modelling of two spanned symmetrical cable-stayed bridge with H-type pylon and its validation using modal analysis in SAP2000. In the present work, the First order second moment (FOSM) method is used for seismic reliability analysis. The seismic reliability analysis of the bridge deck and tower was done with or without vehicular loading when subjected to El-Centro time history in longitudinal and transverse directions. In the present work, the parametric studies were conducted to study the effect of different parameters such as a change in pylon shape (Four types of pylons are considered), uniform phase lag of ground acceleration and shear wave velocity on seismic reliability. The study reveals that the greater the phase lag, greater is the reliability of the bridge. It also reveals that change in pylon shape has no influence on the reliability of the deck but it has more influence on reliability of tower in which it has been found that inverted Y-shape pylon has maximum reliability. The seismic reliability of both bridge deck and tower was found to be minimum for the soil having minimum shear wave velocity.

Keywords: Cable-stayed bridge · Pylon shape · SAP2000 · Seismic reliability analysis · Shear wave velocity · Time history analysis

1 Introduction

The first model of cable-stayed bridge was proposed by Venetian investor Fausto Veranzio in 15th century (Podonly and Walter 1986). In the recent decades, these bridges have been widely built as they provide (1) long span length; (2) appealing aesthetics; (3) increased stiffness over suspension cable bridges; (4) faster mode of construction (Ren and Obata 1999). These bridges have fascinated the engineering community around the world with the recent development in construction technologies and computer software's like SAP2000.

These bridges have long span length, high pylon, intricated connection between the elements, and fastening systems. This increased length of span and height of pylon make

them susceptible to vibrations due to the wind and/or earthquake loadings. Some notable examples are: (1) failure of connections as well as buckling of cross beams and pier leg at the west pier of bridge (2) failure of cable, girder, pier and pylon of 2-span Ji-Ji Da bridge (Kosa and Tasaki 2003). In order to ensure safety of these bridges dynamic analysis is always preferred to study their behaviour (Nazmy and Ghaffer 1990).

The importance of considering risk of failure in bridge design procedure has been identified a long time ago because the true values for structural properties like strength is never known. The main source of these uncertainties involves (1) randomness and unpredictability of seismic loadings, (2) limitations of software, (3) assumptions for simplifying problems (Khan and Datta 2006). Due to these uncertainties absolute safety of the structure cannot be guaranteed. These uncertainties can be incorporated in the design using the philosophy of probabilistic design methods, wherein the variables are considered as random variables. Since, reliability is defined as the probability of survival of the structure under the given prevailing conditions. So, the present work focuses on the reliability analysis of the bridge components i.e. deck and tower when subjected to ground excitation.

Extensive researches have been conducted on substantial cable-stayed bridges to understand their behaviour and performances against seismic excitations. Ren and Obata (1999) studied a four-span cable stayed bridge. The study was oriented towards the effect of geometric and material non-linearity on seismic responses considering four cases namely, (1) small deformation and linear elastic material, (2) linearity in material and nonlinearity in geometry, (3) small deformation and nonlinear material, and (4) geometric and material nonlinearity. The material was found to be elastic under seismic excitation. It also verified that geometric nonlinearity had negligible effect on the seismic responses. So, the present work conducts linear time-history analysis excluding the effect of material nonlinearity and geometric nonlinearity for assessment of harp type cable stayed bridge under earthquake loads.

The cables transfer the deck load to the pylons and these pylons transfers to load to the foundations. The axial tension in cables and compressive force in pylons are the primary forces (Calvi and Sullivan 2010). Polepally and Govardhan (2020) studied the seismic behaviour of cable stayed bridge with four different pylon shapes namely Inverted Y type, H-type, A-type, and Diamond type keeping height constant subjected to three different ground excitations Bhuj 2001, Loma Prieta 1989 and El-Centro 1940. The study showed that shape of pylons has great influence on seismic behaviour of cable-stayed bridge. The present work considers the four different shapes of pylon.

In short span bridges, it is assumed that all the supports are excited simultaneously, i.e., they are under uniform excitation. Considering this assumption, the present study uses the effect of uniform phase namely, earthquake excitation is reaching all the supports simultaneously with same phase lag. However, this assumption would not be applicable for long span harp type cable-stayed bridges. Therefore, spatial effects such as wave passage effect, incoherence effect, and foundation effect cannot be disregarded for long span harp type cable-stayed bridges. The causes behind such effects are as follows –

- Seismic waves when travel from one support to other does not arrive at the same time at all supports. This causes wave passage effect (Kiuregihan and Neuenhofer 1992),

- The refraction and reflection in an anisotropic medium make the ground excitation to lose its consistency. This loss in consistency of ground excitation is known as incoherence effect. This may also cause the superposition of waves which are arriving from farther sources (Kiureghian and Neuenhofer 1992),
- Foundation and soil may not vibrate simultaneously at same frequency due to different flexibility. This effect is known as foundation effect (Sextos 2005).

For time history analysis of long span harp type cable stayed bridges, non-uniform excitation namely, same excitation with different phase lag, should be considered at different supports. In the present work, only the effect which considers delayed arrival of waves i.e., wave passage effect is considered.

Reliability analysis is generally termed as finite element reliability analysis (Balomenos and Pandey 2016) as it is essential to carry out reliability analysis with finite element analysis. The present study uses SAP200 (i.e., finite element software) for seismic analysis whose results have been used further for calculating reliability of the bridge.

2 Method of Reliability Analysis

The present study uses the first-order second moment reliability method (FOSM). It provides a simple strategy that can be used directly to get the reliability index (Ranganathan 1999). In this method, random variables are characterized by their first moment (namely, mean) and second moment (i.e., variance). This method has been described below -

Let, R and S are two basic variables for which the limit state surface equation can be defined as-

$$g = R - S \quad (1)$$

Here,

g – Margin of safety

R – Resistance

S – Load effect

Some percentage of the ultimate bending strength of the bridge cross-sections is considered as the resistance of the bridge i.e., R and the bending moments caused by the earthquake loadings in the bridge elements were taken as the load effect i.e., S .

From above equation, the structure is said to be failed if $R < S$. Therefore, probability of the failure of the bridge P_{fb} is expressed as -

$$P_{fb} = P(R < S) = P(R - S < 0) = P(g < 0) = P\left(\frac{R}{S} < 1\right) \quad (2)$$

The chances of failure depend on the probability distribution of R and S . Let, probability density function of R is $f(R)$ and that of S is $f(S)$. These functions could be normal or lognormal distributions. Assuming that R and S are independent random variable, the probability of failure can be given by -

$$P_{fb} = \int_{-\infty}^{\infty} \left[\int_R^{\infty} f(S) dS \right] g(R) dR \quad (3)$$

The reliability of the bridge is defined as the probability that bridge will perform its required function for which it is designed under operating conditions (Harr 1984). The reliability is the complement of the risk i.e., the probability that loading will not exceed the resistance capacity.

$$R = P(S \leq R) = 1 - P_{fb} \quad (4)$$

In general, the above integrals should be calculated using numerical methods. If R and S are statically independent and normally distributed, then safety margin i.e., g , also would be a normally distributed random variable. In this case, the mean value and standard deviation of g are defined as –

$$\mu_g = \mu_R - \mu_S \quad (5)$$

$$\sigma_g = \sqrt{\sigma_R^2 + \sigma_S^2} \quad (6)$$

where, μ_g , μ_R and μ_S are mean values of g , R and S respectively; and σ_g , σ_R and σ_S are standard deviations of g , R and S respectively.

The normal standard variate z can be defined as $\frac{g - \mu_g}{\sigma_g}$, if the safety margin is normally distributed. Subtracting μ_g from both sides of inequality and dividing by σ_g in Eq. 2. It can be seen that –

$$P_{fb} = P\left(\frac{g - \mu_g}{\sigma_g} < \frac{0 - \mu_g}{\sigma_g}\right) = P\left(z < \frac{-\mu_g}{\sigma_g}\right) = P_Z\left(\frac{-\mu_g}{\sigma_g}\right) \quad (7)$$

Here, P_Z is standard normal variate function.

3 Description of Bridge and Its Properties

The geometry of Quincy Bayview bridge located in Illinois, USA, has been chosen for the present work. This is because, (i) the detailed geometry and properties of the bridge are given in the paper written by Wilson and Gravelle (1991) and (ii) The free vibration test results that are available in the paper written by Wilson and Liu (1991) have been used to validate the present model. It consists of H-shaped concrete pylon, double-plane fan type cable, and a composite steel-concrete deck with steel floor beams (Wilson and Gravelle 1991). The longitudinal view of the bridge is shown in Fig. 1. The bridge is supported by 56 cables in which 28 cables supports mid span while 14 cables support each side span. The cables are constructed of 6.4 mm diameter wires with an ultimate strength of 1600 MPa. Each tower consists two concrete legs with a 1.20 m thick stiffening wall as shown in Fig. 2. The 14 m wide road deck consists of five longitudinal stringers spaced at 2.20 m as shown in Fig. 3. The detailed description of the bridge can be found in the paper (Wilson and Gravelle 1991; Hariri and Lin 2021).

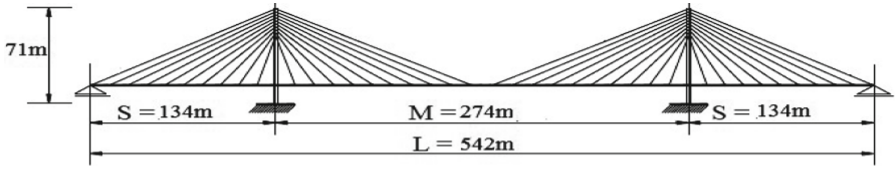


Fig. 1. Longitudinal view of the bridge.

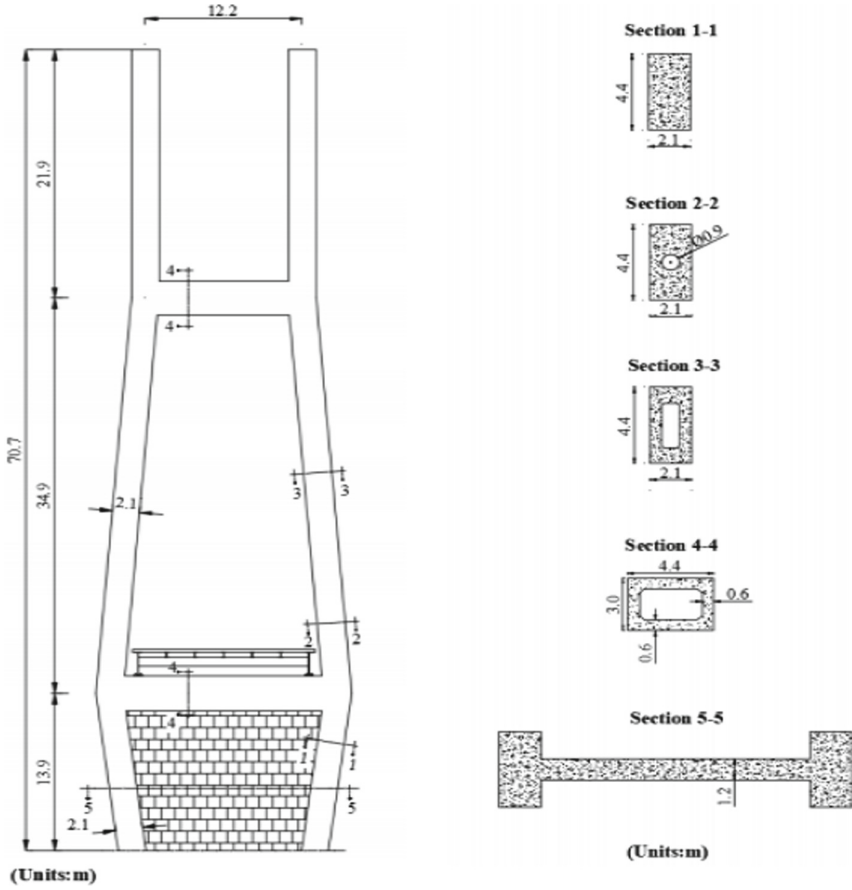


Fig. 2. Geometry of bridge pylon (Hariri and Lin 2021).

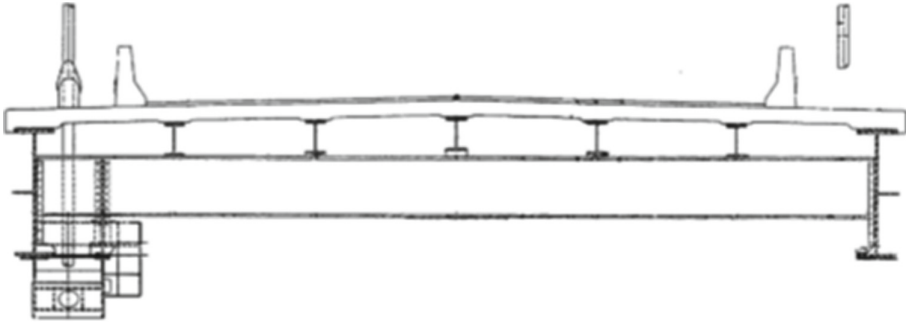


Fig. 3. Cross-section of the bridge deck (Wilson and Gravelle 1991).

4 Seismic Input

The 1940 El Centro earthquake having PGA of 0.319g and PGD of 0.096 m have been used as seismic input in the present study as shown in Fig. 4.

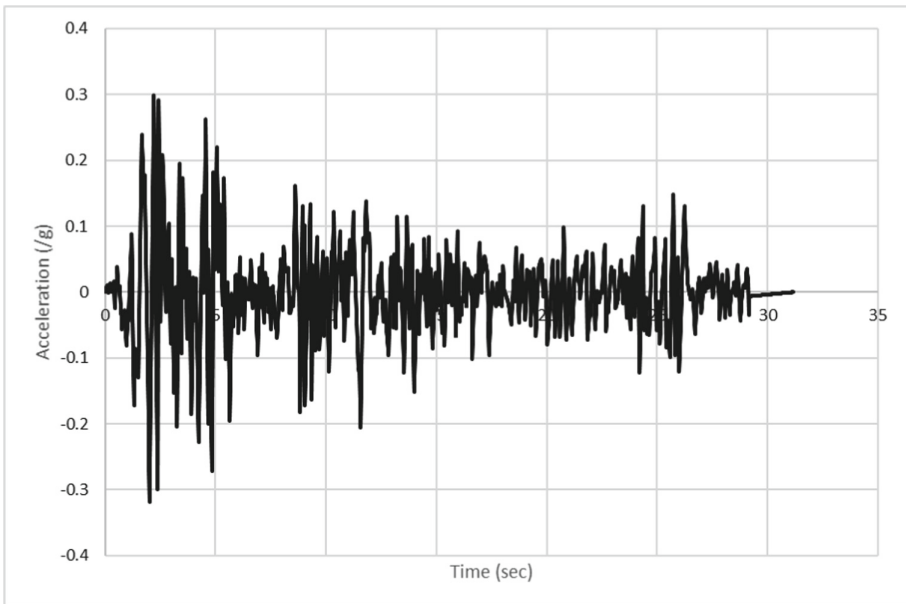


Fig. 4. Ground excitation.

5 Statical Properties of Random Variables

In the present study three random variables are considered which are listed in Table 1. The mean, standard deviation, and coefficient of variations for all the variables are shown in Table 1.

Table 1. Statical properties of random variables

Component	Variable	Mean	Std deviation	COV	Distribution function	References
Load	Earthquake PGA	0.017g	0.125g	0.136	Normal	Pourzeynali and Hosseini-zhad (2009)
	Earthquake Magnitude (Richter)	2	6	0.333	Normal	
	Dead Load and Live Load (kN/m)	110	11	0.10	Normal	Bartlett et al. (2003)

6 Finite Element Modelling of the Bridge

The analytical models as shown in Fig. 5, of the bridge includes all components that affect the strength, mass, deformability and stiffness of the structure. The bridge structural system consists of cables, pylons, deck slab, struts, transverse and longitudinal beams. The non-structural elements that do not affect much the bridge behaviour are not modelled. The tower and deck were modelled used beam element while cables are modelled used truss element. Moreover, deck was modelled as a single central spine with offset links to accommodate lumped masses and cable anchor points. Table 2 shows the lumped masses which are assigned in SAP2000 (Wilson and Gravelle 1991; Hariri 2018).

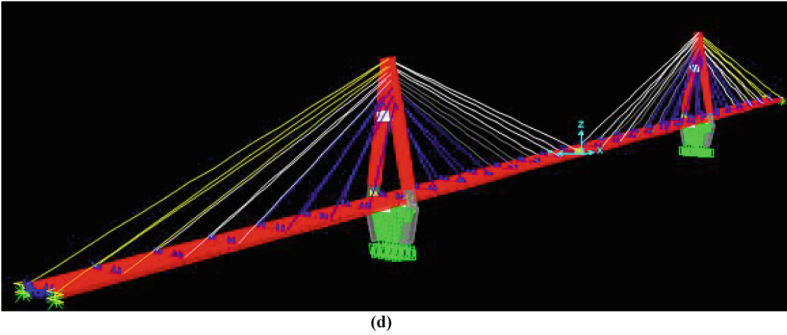
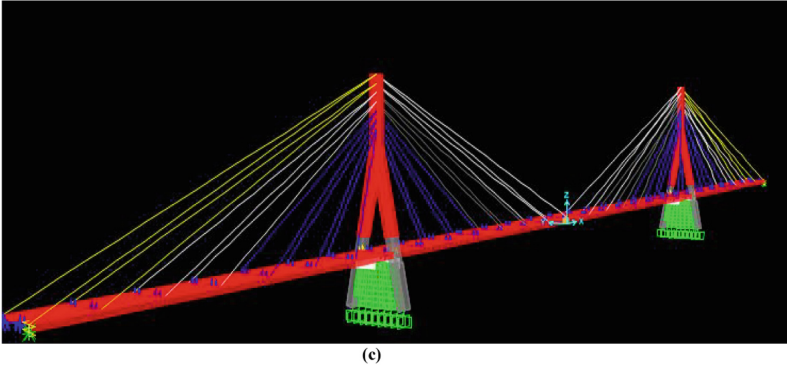
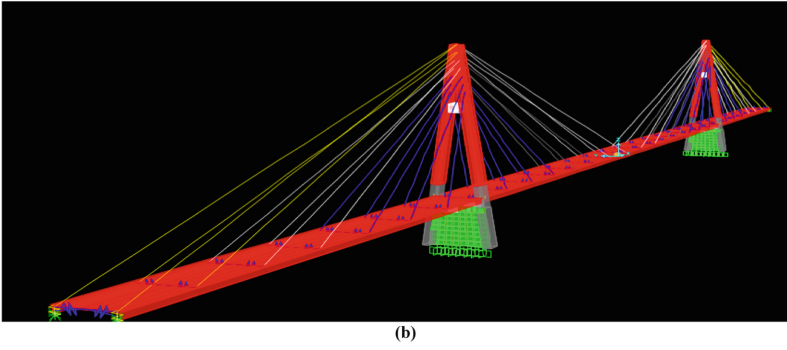
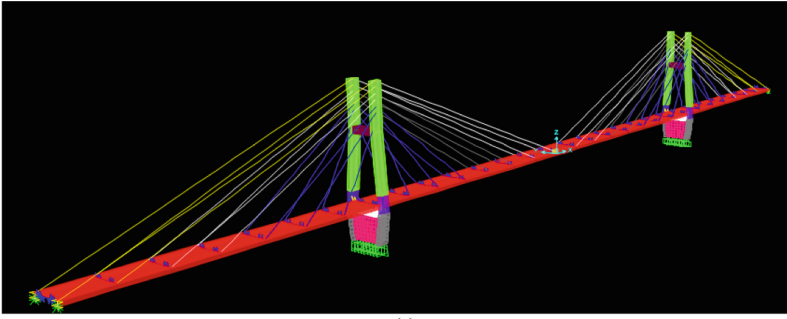


Fig. 5. (a) SAP2000 model with H-shape pylon. (b) SAP2000 model with A shape pylon. (c) SAP2000 model with inverted Y- shape pylon. (d) SAP2000 model with diamond shape pylon.

Table 2. Lumped translation mass assigned in SAP2000 (Hariri 2018)

Element	Weight (kN/m)	Lump weight	
		Main span (kN)	Side span (kN)
Slab	76.33	1063.0	1115.5
Stringer	1.57		
Girder	9.50		
Barrier	6.52		

7 Numerical Study

7.1 Validation of the Present Model

Figure 6 shows the comparison of first three mode shapes of the present model with the test results from the paper written by Wilson and Liu (1991). Similarly, Table 3 shows the comparison of first vertical bending mode and first mode involving coupled and torsional motions of the deck with the results of modal frequencies given in the paper written by Wilson and Gravelle (1991). The model can be used for further analysis as the variation between the modal frequencies is less than 10%.

Table 3. Comparison of modal frequencies

Mode shape	Modal frequencies of present model (Hz)	Modal frequencies given by Wilson and Gravelle (1991) (Hz)
First vertical bending mode	0.3896	0.371
First mode involving coupled transverse and torsional motions of the deck	0.588	0.577

7.2 Effect of Change in Pylon Shape

Figure 7 shows the effect of change in pylon shape on the variation of reliability. Four different types of pylon shapes are considered which are namely H-shaped, Inverted Y-shape, Diamond shape and A-type shape pylons. It is can be seen that change in pylon shape has less or negligible effect on the reliability of deck while H-type pylon yields minimum reliability of tower in comparison to others. This may be due to the fact spread out pylons from pylon base or girder level reduces sag of cables and oscillations of cable during earthquake. Also, inclined legs produce delay in peak occurrence in all response quantities. Hence, greater the inclination of leg greater will be the delay. It is also evident that the reliability of both bridge deck and tower are more when earthquake was applied

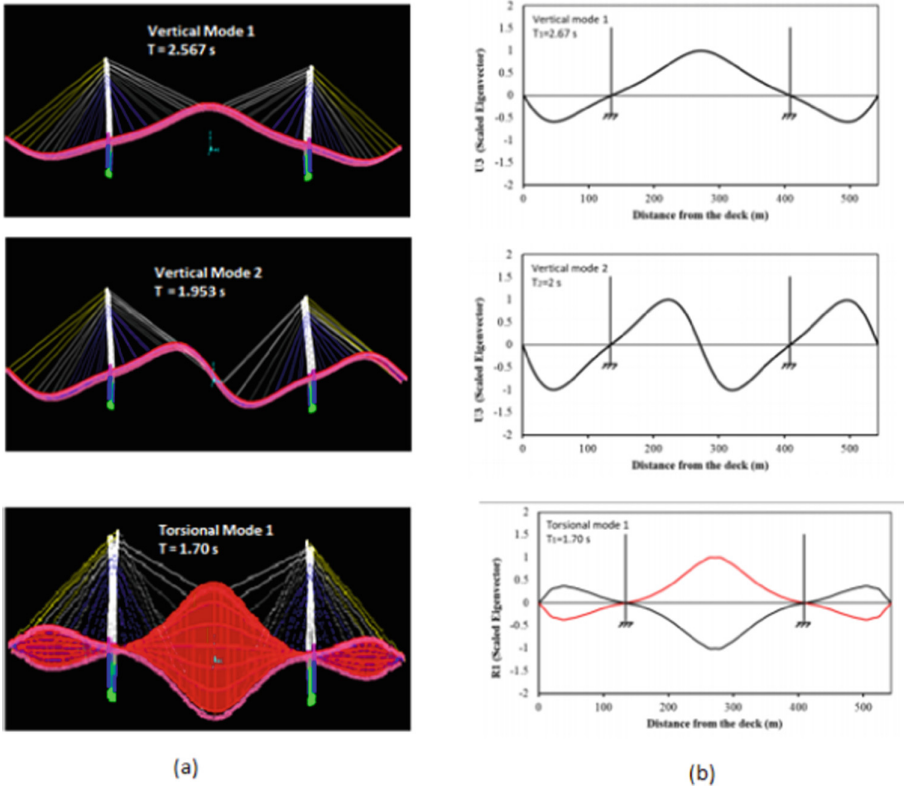
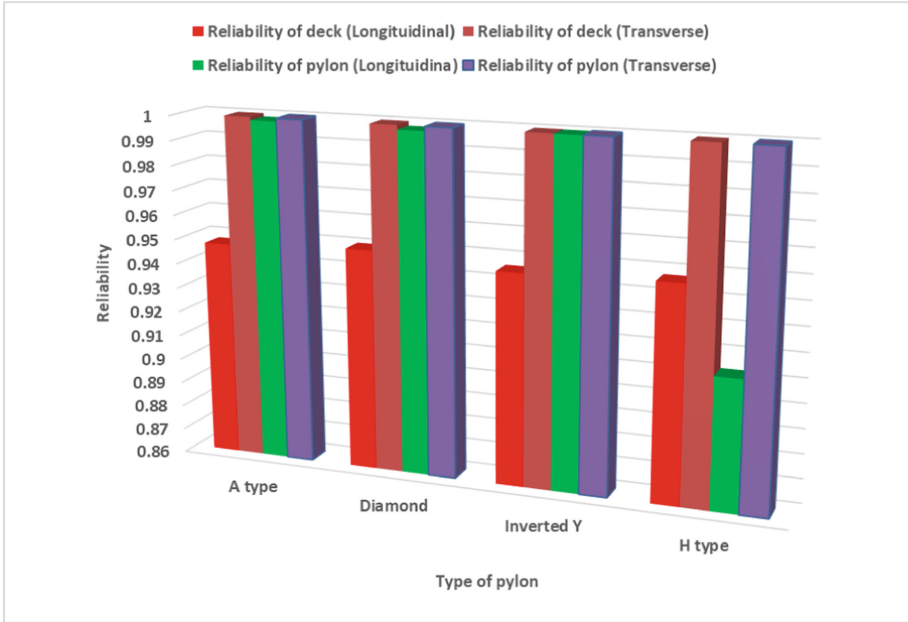


Fig. 6. Comparison of mode shapes of the (a) present model, and (b) test results of Wilson and Liu as given in Hariri and Lin (2021).

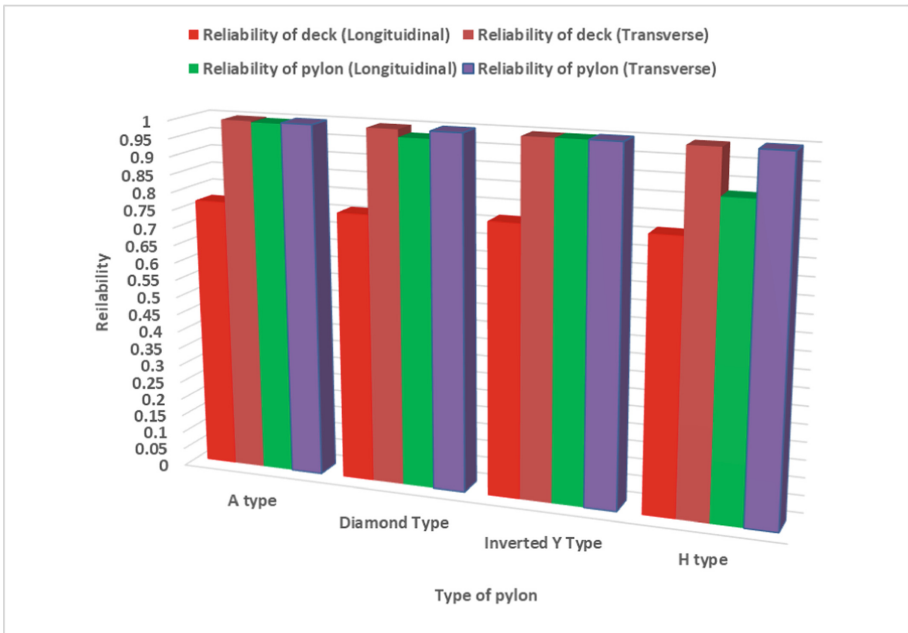
along transverse direction of the bridge. It is also evident that the reliability of deck is relatively more when vehicular loading was not considered.

7.3 Effect of Uniform Phase Lag

Figure 8 shows the effect of uniform phase lag on the variation of reliability. It is evident from the figure that, with increase in phase lag the reliability is decreasing. The probable reason behind such variation is that with lagging of time history peak values will not be acting on the structure, so the reliability will decrease accordingly. It is also evident that the reliability of both bridge deck and tower are more when earthquake was applied along transverse direction of the bridge. It is also evident that the reliability of deck is relatively more when vehicular loading was not considered.

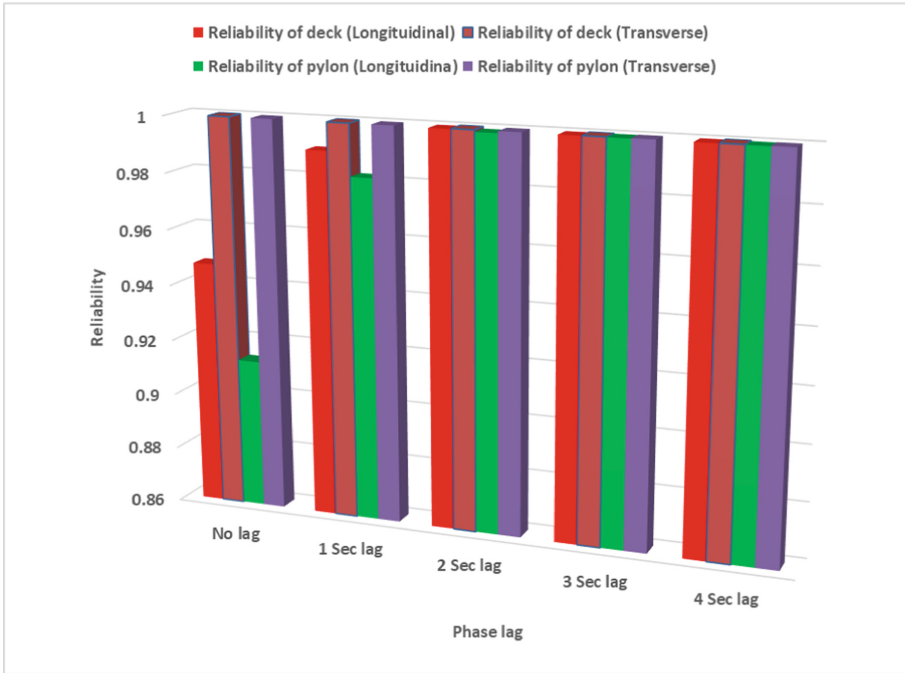


(a)

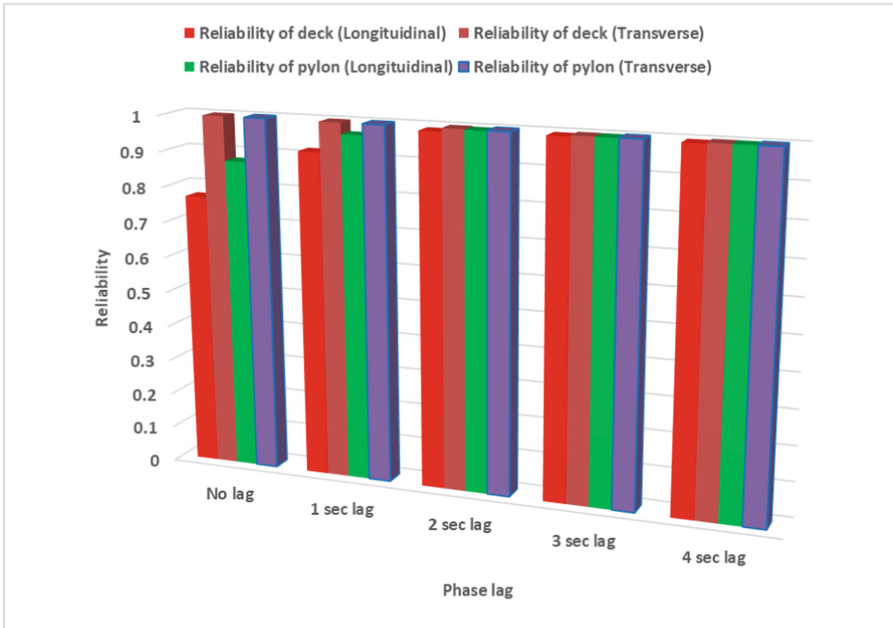


(b)

Fig. 7. (a) Effect of shape of pylon on reliability of the bridge without vehicular loading. **(b)** Effect of shape of pylon on reliability of the bridge with vehicular loading.

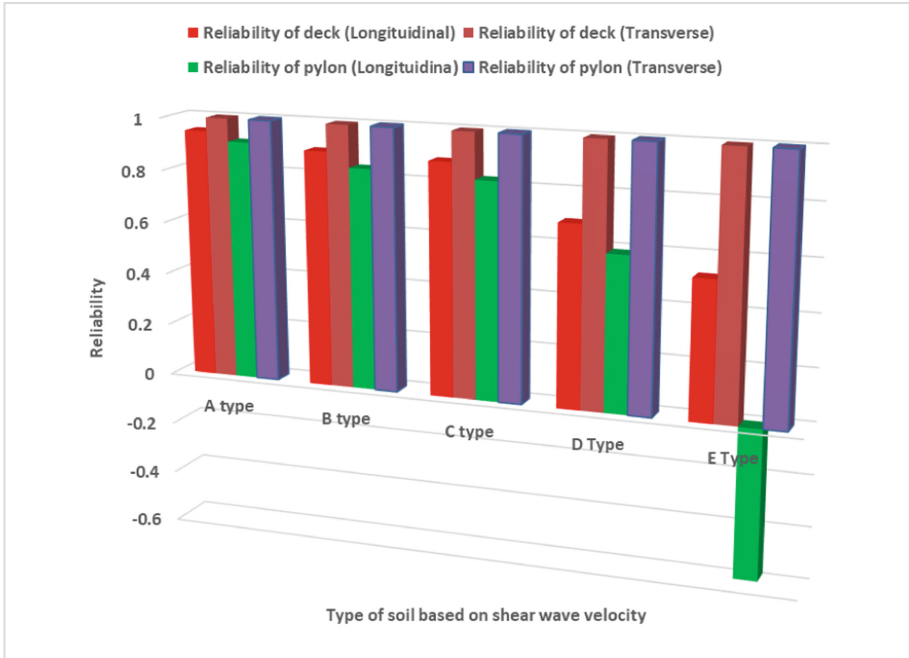


(a)

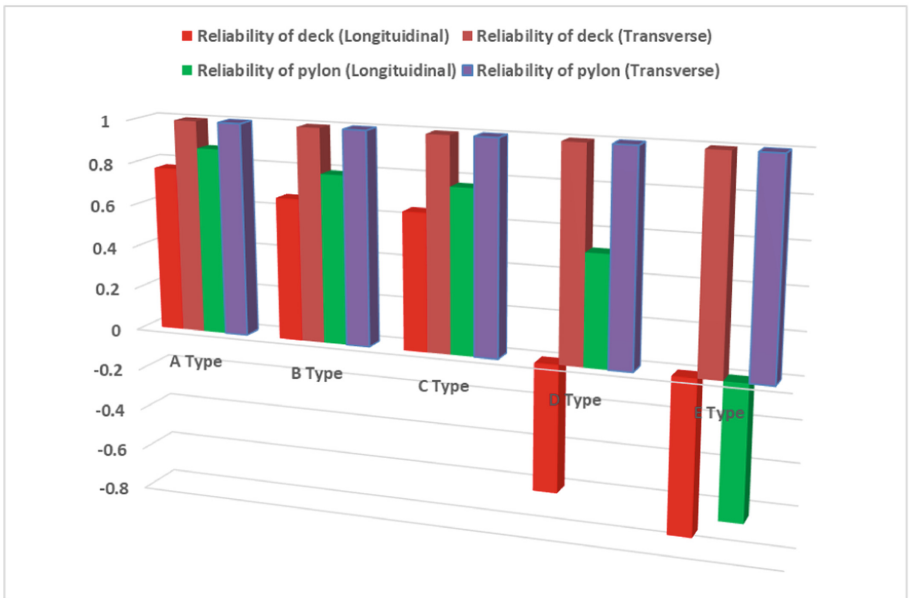


(b)

Fig. 8. (a) Effect of uniform phase on reliability of the bridge without vehicular loading. (b) Effect of uniform phase on reliability of the bridge with vehicular loading.



(a)



(b)

Fig. 9. (a) Effect of shear wave velocity on reliability of the bridge without vehicular loading. **(b)** Effect of shear wave velocity on reliability of the bridge with vehicular loading.

7.4 Effect of Shear Wave Velocity

Figure 9 shows the effect of shear wave velocity on the variation of reliability of the structure. It is evident from the figure that, with decrease in shear wave velocity the reliability of deck and tower both are decreasing. This may be due to the fact that, lesser shear wave velocity lesser stiffer the soil and Hence, greater will be the stresses. It is also evident that the reliability of both bridge deck and tower are more when earthquake was applied along transverse direction of the bridge. It is also evident that the reliability of deck is relatively more when vehicular loading was not considered.

8 Conclusions

Present study adopted the model of harp type cable stayed bridge with different types of pylon shapes and different loading conditions. In this study, El Centro time history was considered in both longitudinal and transverse direction of the bridge. The following are the conclusions of the present study -

1. The natural frequencies of the bridge were obtained through modal analysis using SAP2000. The natural frequencies were not found closely spaced i.e. differ from each other by more than 10%.
2. The seismic reliability of bridge deck and tower were found to be increasing with increase in phase lag. This may be due to the fact that with increase in phase lag energy transmitted by the ground acceleration decreases. Hence, the reliability of the bridge will be maximum for 4 s phase lag and minimum when there is no phase lag.
3. The seismic reliability of bridge deck was found to be unaffected (or slightly less varied) with the change in pylon shape. While for bridge tower it was found to be varying considerably with change in pylon shape. It was found that inverted Y-shape pylon provides maximum reliability while H-type pylon provides minimum reliability. This may be due to the fact spread out pylons from pylon base or girder level reduces sag of cables and oscillations of cable during earthquake. Also, inclined legs produce delay in peak occurrence in all response quantities. Hence, greater the inclination of pylon legs, greater will be the delay in the arrival of the earthquake.
4. The seismic reliability of both bridge deck and tower was found to be minimum for soft soils and maximum for Hard soils. This may be due to the fact that in hard soil seismic wave will travel faster producing minimum delay in arrival of waves to pier from abutment.
5. The reliability of bridge deck was found to be lesser than that of tower when vehicular loading was considered. While it was more without vehicular loading. Hence, it can be concluded that the reliability of the bridge deck depends on the loading and equilibrium conditions of the bridge.
6. It can also be concluded that the earthquake excitation along longitudinal direction results in lesser reliability of the both bridge deck and tower, in comparison to when applied along transverse direction.

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