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THE INVESTIGATION OF THE EFFECTS OF VERTICAL EARTHQUAKE COMPONENT ON SEISMIC RESPONSE OF SKEWED REINFORCED CONCRETE BRIDGES

Saman Mansouri

Islamic Azad University, Dezful Branch, Dept. of Civil Engineering, Iran.
e-mail: samanmansouri@ymail.com

ABSTRACT: In this study, the effects of the vertical ground motion on the seismic response of the skewed RC bridges were investigated. First, the considered bridge was modeled. Then, the nonlinear time history analysis was used to evaluate the seismic response of the skewed RC bridge at two states with and without applying the effect of the vertical ground motion. The results of studies indicated that the application of the vertical ground motions in the seismic design of bridges was very important. Also, the application or non-application of vertical ground motions had no significant effect on the amount of base shear of the studied RC skew bridge. Moreover, the application of the vertical ground motions caused a significant increase in the bridge response in its vertical direction than non-application.

KEYWORDS: Skewed RC Bridge, Vertical Ground Motion, Vertical Motions, Seismic Response.

1 INTRODUCTION

The review of the earthquakes in recent decades has indicated that a large number of bridges are damaged significantly by earthquakes. Regarding the strategic role of the bridges in the transportation system, bridges closure can lead to different damages. Therefore, the study of the seismic response of bridges from different aspects is of particular importance.

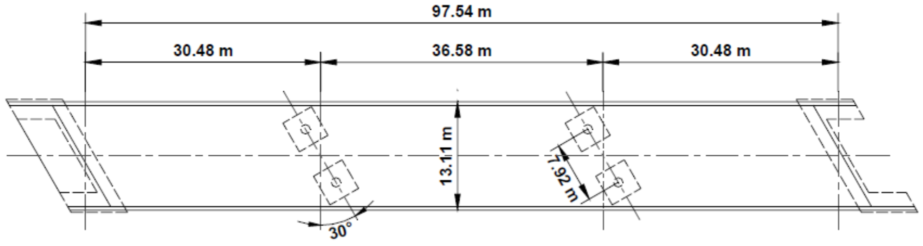
Uncertainty in the parameters of strong ground motions has caused the effects of each of these parameters on the seismic response of bridges to be always investigated by researchers. The effects of vertical ground motions on different structures as one of the important characteristics of the earthquakes have always been paid attention to. Recently, many different studies have been conducted on the effects of the vertical component of earthquakes on the seismic response of bridges. For instance, Papazoglou and Elnashai (1996), in the examination of the many bridge failures affected by Kobe and Northridge earthquakes, found that the collapse of the most bridge's columns was due to the unpredicted increase of axial force of columns caused by the vertical component of the earthquake. Yu et al. (1997) investigated the effects of vertical ground motion on the seismic response of bridges with the focus on the geometry shape. They found that the vertical ground motion could have considerable effects on the large-span bridges, and this problem was more critical for side supporters. Button and Cronin (2002) studied the effects of vertical motion on the seismic response of various bridges. The results of their study indicated that applying the effect of vertical motion was very significant in the seismic design of the bridges. Moreover, Yang and Lee (2007) found that the effect of vertical motion could be applied as the coefficient of the horizontal component of earthquakes on the structures. Kunnath and et al. (2008) found that applying the effect of near-fault vertical ground motions increased the axial force in the columns of bridges significantly. Rahai and Arezoumandi (2008) examined the seismic response of one of the columns of a bridge at two statuses, with and without the effect of the vertical ground motions. Their results indicated that the application of the effect of the vertical ground motions increased the axial force of the columns than its non-application. In an experimental study, Kim et al. (2011) compared the seismic response of a column of a bridge in two different conditions. In the first case, the column was only under the effect of the horizontal ground motions, and in the second case, the column was under the effect of horizontal and vertical ground motions simultaneously. The results of the studies indicated that the potentiality of seismic vulnerability of the column against the simultaneous excitation of horizontal and vertical ground motions was far more than the state that column was under the effect of the horizontal ground motion. Wilson et al. (2015) examined the effects of the vertical ground motion on the seismic response of the curved reinforced concrete and the skewed reinforced concrete bridges. The results of their studies indicated that the application of the effect of vertical ground motion increased the seismic vulnerability potential of bridges than its non-application. Moosavi et al. (2016) studied the effects of the vertical ground motion on the seismic response of an arched bridge. They found that the axial forces amplification factors in nonlinear and linear time history analyses were approximately equal. Therefore, the linear time history analysis could be used to investigate the effects of the vertical ground motion on the changes of bridge axial force. Dangol and Suwal (2016) studied the effects of the vertical component of earthquakes on the seismic response of reinforced concrete arched bridges. They found that the effect of the vertical ground motion had no significant effect on the horizontal displacement of the studied bridges. Nevertheless, the effects of the vertical ground motion could have a significant effect on the axial force of the RC arched bridges than its non-application. In the study of Yang et al. (2019), shake table tests were performed on a single-frame bridge model with adjacent abutments subjected to uniform ground excitations. Bridges with different skew angles, i.e., 0°, 30°, and 45°, were considered. The pounding behavior was observed using a pair of pounding and measuring heads. The results revealed that poundings could, indeed, influence the responses of skewed bridges in the longitudinal and transverse directions differently and thus affect the development of the girder rotations. Ignoring pounding effects, the 30° skewed bridges could experience more girder rotations than the 45° skewed bridges. With pounding, the bridges with a large skew angle could suffer more opening girder displacements than straight bridges. In the paper of Estekanchi et al. (2019), the influence of the excitation angle on the Endurance Time (ET) analysis of skewed slab-on-girder bridges was studied. They showed that for the skewed bridges, the critical excitation angle was dependent on the hazard level in addition to the skew angle. On the other hand, for the straight bridges, the critical excitation angle remained the same at all considered hazard levels. Besides, the seismic responses of bridges with higher skew angles were, in general, higher than those with lower skew angles. This confirmed the vulnerability of skewed bridges in comparison to straight ones at all hazard levels. Chen et al. (2019) showed that the skewed and curved bridges have very different seismic responses on different columns under both seismic and traffic loads, such as transverse moments due to the curved and skewed nature. The demand and capacity ratio of the longitudinal moments was much higher than other seismic response, indicating limited safety reserve. Besides, there were large pounding forces between the girder and abutment, causing probably considerable damage to the concrete and expansion joints.

In addition to the studies mentioned above, standard loads for bridges ((Iranian code No. 139)-(2000)) introduced the method mentioned in the road and railway bridges seismic-resistant design code ((Iranian code No. 463)-(2008)) to apply the effects of earthquakes in the seismic design of bridges as the design reference. The estimation's methods of the seismic response of the structures at both transverse and longitudinal directions according to Iranian codes No. 463 and No. 2800 (3th edition) was as the following: the horizontal component of an earthquake with 30% of other horizontal component and 30% of vertical component were summed up to estimate horizontal response of structure; and also, the vertical component of an earthquake with 30% of the longitudinal and transversal component were summed up to estimate the vertical response of the structure. Nonetheless, the "Iranian code of practice for the seismic-resistant design of building (Standard 2800, 4th edition)" stated that the vertical and horizontal components of an earthquake should not be summed up, but they should be applied separately on the structure. In the code of the Caltrans seismic design criteria (SDC, 2006), to determine the effect of the vertical ground motion on the bridges, a vertical load equal to 25% of dead load toward the up and down of the structure was considered.

Although many studies have been conducted by researchers in recent years concerning the effects of the vertical ground motion on the seismic response of the bridges, some of which were mentioned, a comprehensive study has not been done thus far to investigate the vertical ground motion on the skewed bridges. Therefore, the effects of the vertical ground motion on the seismic response of the skewed reinforced concrete bridges were investigated in this study. In this study, first, the considered bridge was modeled. Then, the nonlinear time history analysis was used to evaluate the seismic response of a skewed RC bridge at two states with and without applying the effect of the vertical ground motion.

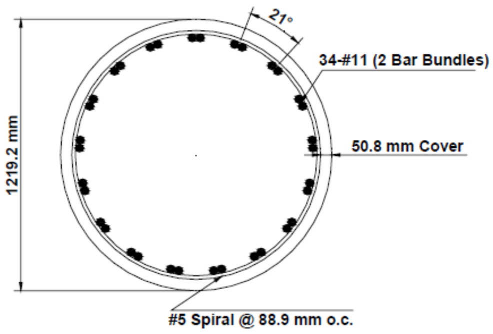
2 THE STUDIED BRIDGE

A three-span reinforced concrete bridge was examined in this study. The length of lateral and middle spans was 30.48m and 36.58m, respectively. The substructure elements were oriented at a 30° skew from a line perpendicular to a straight bridge centerline alignment, as shown in Fig. 1 (a).

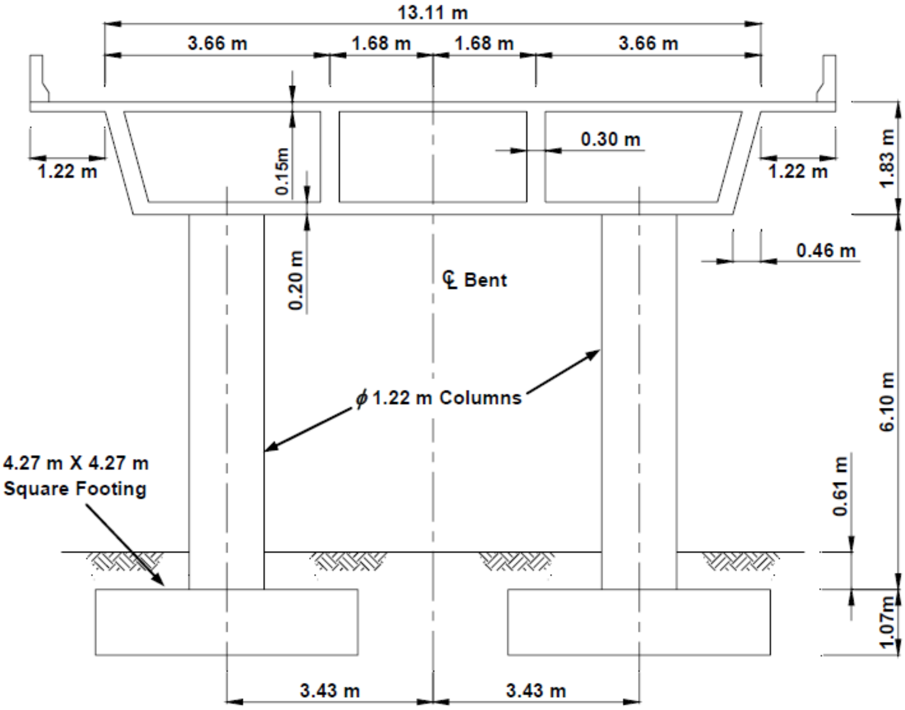


(a) Plan view

(b) Elevation



(c) Pier section



(d) Cross-section of bent

Figure 1. Prototype structure, FHWA No. 4 (1996)

3 THE CHARACTERISTICS OF SELECTED EARTHQUAKES

The selected accelerograms were related to the Chi-Chi, Landers, Loma Prieta, Northridge, Parkfield, San Fernando, and Tabas earthquakes, which were selected and scaled according to Iranian Standard No. 2800.

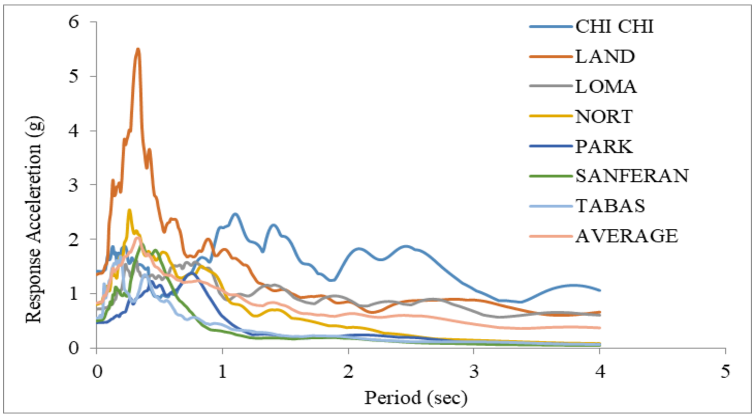


Figure 2. The spectrums of selected earthquakes

Characteristics, including the magnitude, the distance from the fault, and the mechanism of the site, were considered in the selection of the accelerograms. These accelerograms were related to the stations registered at the distance of 20 to 60 kilometers from the fault with no near-fault earthquakes characteristics, such as forward directivity and fling-step. Furthermore, the magnitude of all the selected earthquakes was between 6.5 and 7.5 Richter. The spectrum of each earthquake is shown in Fig. 2, and the spectrum of Iranian Standard No. 2800 and spectrum of earthquakes' mean is indicated in Fig. 3.

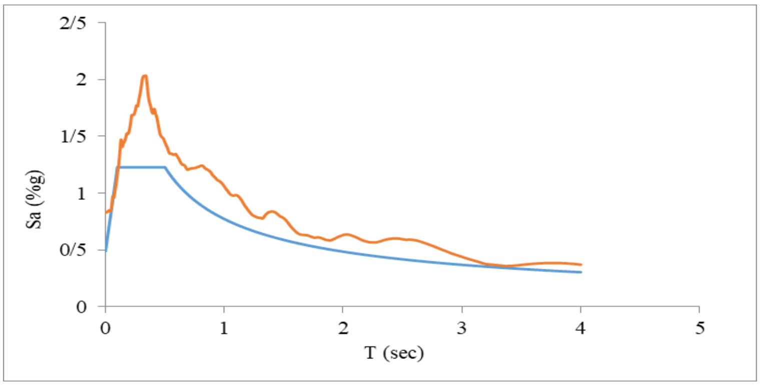


Figure 3. The comparison of the spectrum of Iranian Standard No. 2800 with earthquakes' mean spectrum

4 NONLINEAR TIME HISTORY ANALYSIS

The seismic response of the studied bridge was investigated in the four cases of different loading. In the first case, the studied bridge was only affected by two components of horizontal orthogonal. In the second case, the response of the bridge was examined under the influence of two components of horizontal orthogonal and dead load. In the third case, the studied bridge was evaluated in terms of two components of horizontal orthogonal and vertical ground motions. In the last case, the studied bridge was subjected to the motions of two components of horizontal orthogonal and vertical ground motions, together with the dead load.

In this research, the dead load was applied to the structure dynamically through the spectrum of the ramp. It should be noted that the four cases of loading were applied to the Tabas earthquake (including, TABAS1, TABAS2, TABAS3, and TABAS4) and for the Landers earthquake (including, LAND1, LAND2, LAND3, and LAND4). The results of the base shear of the studied bridge under the influence of Tabas and Landers earthquakes in all four cases of loading are presented in Fig. 4.

According to Fig. 4, the results of the nonlinear time history analysis showed that the application or non-application vertical ground motions did not affect the base shear of the studied bridge so that in the all loading combinations, the base shear of the bridge did not change for each discussed earthquake in both horizontal directions.

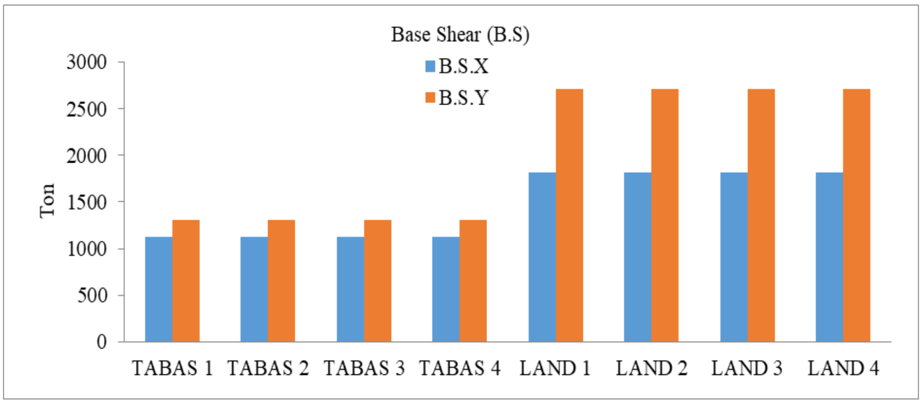


Figure 4. The results of base shear of the bridge in longitudinal (X) and transversal (Y) directions under the influence of Tabas and Landers earthquakes

The vertical axial force of the bridge for each loading combination is presented in Fig. 5.

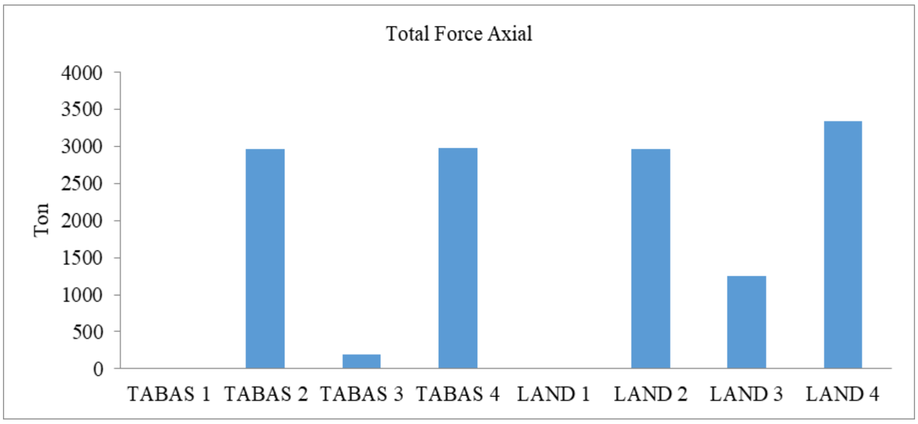


Figure 5. The results of the vertical axial force of the bridge under the influence of Tabas and Landers earthquakes

According to Fig. 5, the results of studies indicated that the application of the vertical ground motion could affect the vertical axial force of the studied bridge considerably than its non-application so that in the first loading combination, where only the components of horizontal orthogonal of the earthquake were applied to the bridge, the response of the structure was negligible in its vertical direction. This result was the same for both Tabas and Landers earthquakes.

The noticeable point was the vertical response of the bridge against the second loading combination. In the second loading combination, the vertical response of the bridge against the dead load was equal to 2963 tons.

Since the dead load only was applied to the vertical direction of the bridge, this result was the same for both loading cases of the Tabas and Landers earthquakes.

In the third loading combination, the structure was under the influence of two components of horizontal and vertical ground motions. The vertical axial response of structure against Tabas and Landers earthquakes was 197.4 and 1247 tons, respectively. The significant difference of vertical axial force of bridge affected by two earthquakes indicated that only the application of vertical ground motions was insufficient. Thus, in order to reduce the significant difference in the vertical axial force of the bridge, the recognition of earthquakes' characteristics while paying attention to the realistic features of the structure and its site were of particular importance.

In the fourth loading combination, which the structure was under the influence of two horizontal orthogonal components, the vertical component of the earthquake, and dead load, the vertical axial response of the structure against Tabas and landers earthquakes was 2973 and 3339 tons, respectively. This suggested that the simultaneous application of the dead load and effect of the vertical component of the earthquake to estimate the realistic response of the structure in its vertical direction were of particular importance.

The significant difference in the seismic response of the studied structure against the Tabas and Landrace earthquakes with magnitudes of 7.3 Richter showed that the application of the effect of vertical ground motions needed a comprehensive understanding of earthquakes characteristics, and its mere application in the seismic design of structures was insufficient regardless of the importance, efficacy, and comprehensive understanding of the site's characteristics. Therefore, the characteristics of Tabas and Landers earthquakes were examined in Section (5). To check the deck displacement, three points on the surface were determined, each of which was placed in the center of the related spans. A view of the selected points is shown in Fig. 6:

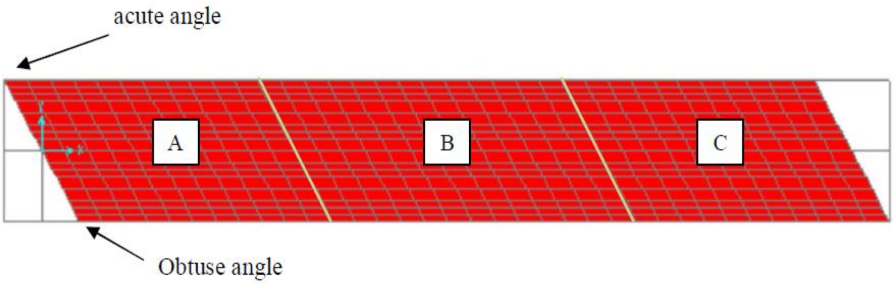


Figure 6. A view of the studied points on the deck's surface of the studied bridge

In Fig. 7, the results of the horizontal displacement of point (A) are presented for each of the four groups of Tabas and Landers earthquakes.

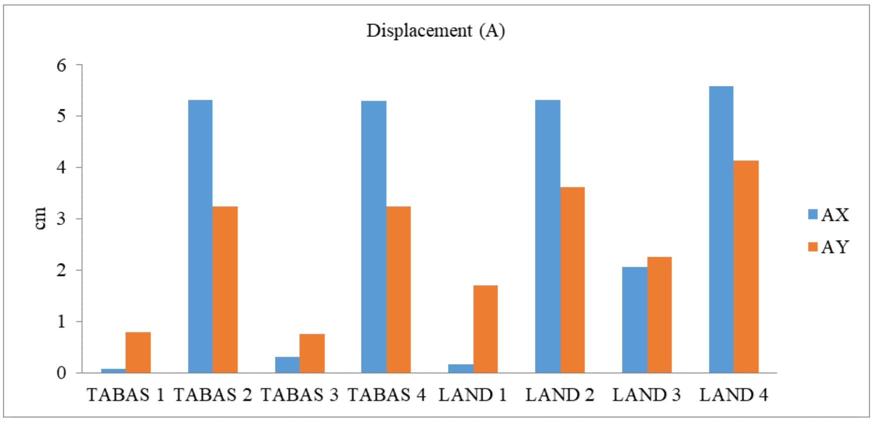


Figure 7. The maximum lateral displacement of point A in longitudinal (X) and transverse directions (Y)

Since the first and third applied loading groups to the structure were two and three components of the earthquake, respectively, and according to the obtained results in Fig. 7, it was clear that the application or non-application of vertical ground motions of Tabas and Landers had no significant effect on the lateral displacement of point (A).

By comparing the obtained results of the lateral displacement for point (A) affected by the second and fourth loading groups, it was found that the values of lateral displacement of this point affected by loading combinations of the discussed group were approximately equal.

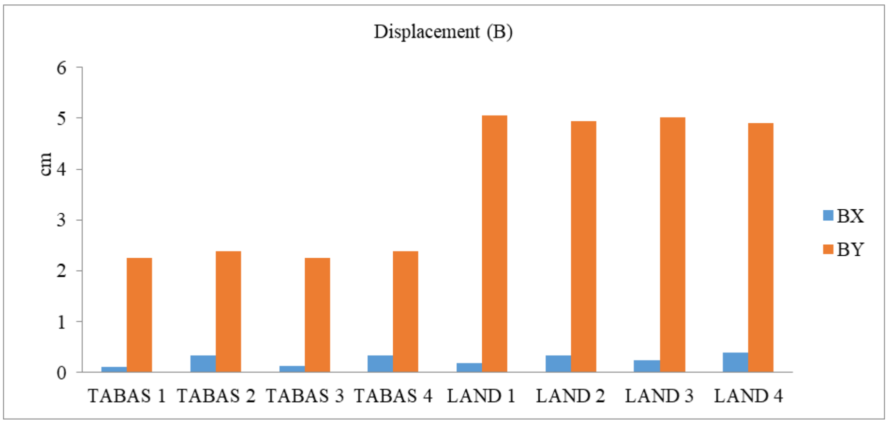


Figure 8. The maximum of the lateral displacement of point B in longitudinal (X) and transversal directions (Y)

The results of the horizontal displacement of point (B) are presented for each of the four loading groups of Landers and Tabas earthquakes in Fig. 8.

The results of studies, according to Fig. 8, indicated that the lateral displacement of point (B) under the influence of all four loading groups of the Tabas earthquake was almost equal. Furthermore, the results of lateral displacements for this point for each of the four loading groups of the Landers earthquake were also approximately equal.

In Fig. 9, the results of the vertical displacement of points (A) and (B) are presented for each of the four loading groups of Landers and Tabas earthquakes.

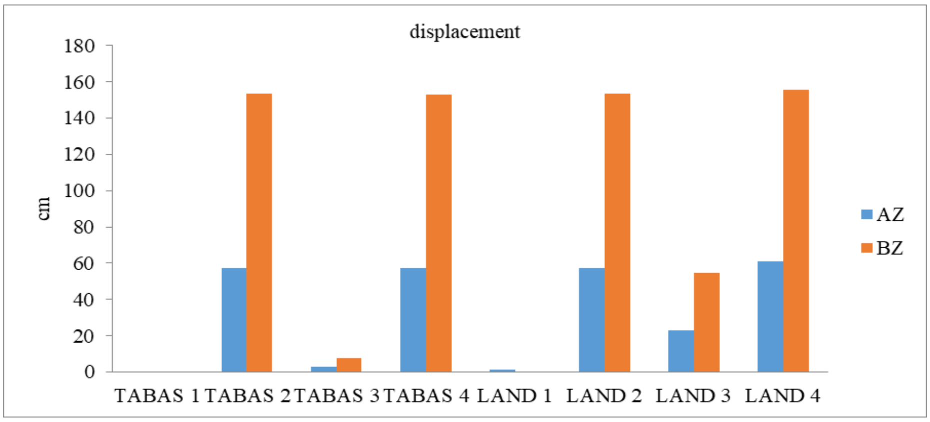


Figure 9. The maximum of vertical displacement of the studied points

According to Fig. 9, in the first seismic loading groups, the excitation did not enter in the vertical direction of the bridge; hence, the vertical displacement of points (A) and (B) was approximately zero. In the third seismic loading group, two horizontal orthogonal and vertical components were applied to the structure. The vertical displacement of points (A) and (B) under the influence of the Tabas earthquake was 3.01 and 7.91 cm, respectively, and under the influence of the Landers earthquake was equal to 22.75 and 54.55 cm. This conclusion could suggest that the vertical component of the Landers earthquake caused a significant vertical displacement in the middle and lateral spans than the Tabas earthquake.

In the second and fourth loading groups, the excitation of two and three-components of the earthquake synchronized with the dead load was applied to the structure, respectively. Regarding the significant weight of the bridge, the application or non-application of the vertical component of the earthquake in this study did not significantly change the amount of vertical displacement of the points.

In Fig. 10, the response history of displacements of the studied points is shown in the transversal direction of the bridge.

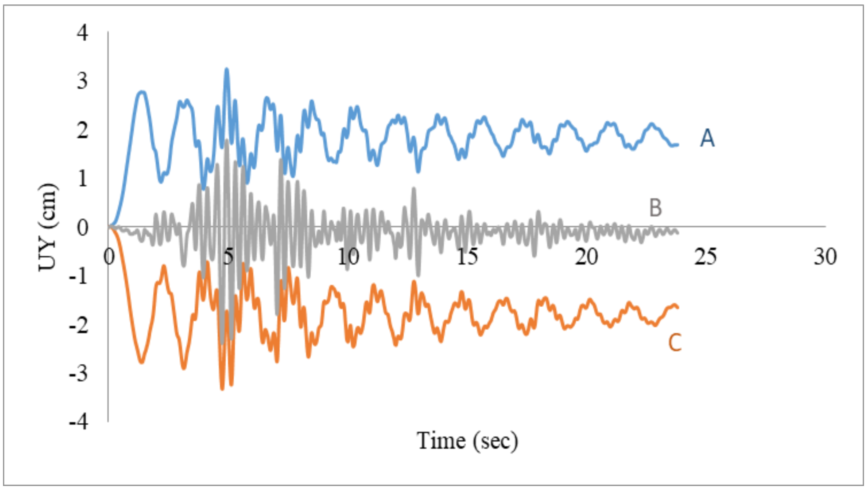


Figure 10. Transversal displacement of the discussed points under the influence of the second loading group of the Tabas earthquake

According to Fig. 10, the results of the transversal displacement of the studied points under the influence of the second loading group indicated that the transversal displacement of the deck in the side spans was directed to its acute angle when the dead load was applied dynamically. Due to the skew angle of the deck and its parallelogram shape, the transversal displacement of the side spans was opposite to each other. In other words, the two side spans of the bridge around its mid-span had clockwise motion.

It should be noted that in the discussed model in the case of irregularity elimination (converting parallelogram shape into a rectangular in the deck of the studied bridge), the transversal displacement opposite to each other in two lateral spans under this type of loading was also disappeared. This shape of the displacement for the fourth loading group could be generalized; nonetheless, it did not apply to the first and third loading groups.

The significant difference in the seismic response of the studied bridge affected by two earthquakes of Tabas and Landers, which were selected based on the requirements of the Iranian codes No. 2800 and 463, indicated that the parameters for the selection of earthquakes and their characteristics should be mainly evaluated. Therefore, these issues are discussed in the next section.

5 DISCUSSION

This section deals with the significant difference reasons in the seismic response of the studied bridge against the Tabas and Landers earthquakes. Furthermore, the conditions of earthquakes' selection and loading combinations presented in some standards for the application of vertical ground motions of earthquakes are discussed.

Figs 11 to 13 indicate the spectrums of horizontal orthogonal and vertical components of the Tabas and Landers earthquakes. The comparison of the related spectrums of the Landers earthquake in Fig. 11 shows that the related spectrum to the vertical component of this earthquake is much greater than its two components of horizontal orthogonal. According to Fig. 12, the comparison of the spectrum of the transitional components of the Tabas earthquake indicates that the spectrum of horizontal orthogonal components related to this earthquake is greater than its vertical component spectrum. The comparison of the vertical components of the Tabas and Landers earthquakes in Fig. 13 shows that the vertical components of the Landers earthquake are greater than the vertical components of the Tabas earthquake.

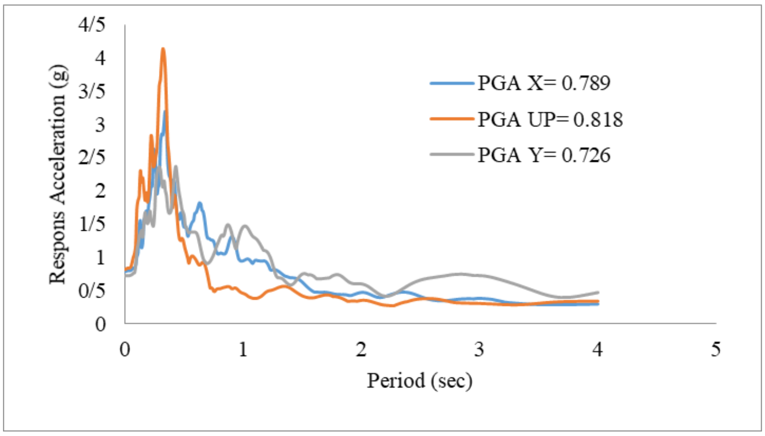


Figure 11. The spectrum of transitional components (including two horizontal orthogonal and vertical components) of the Landers Earthquake

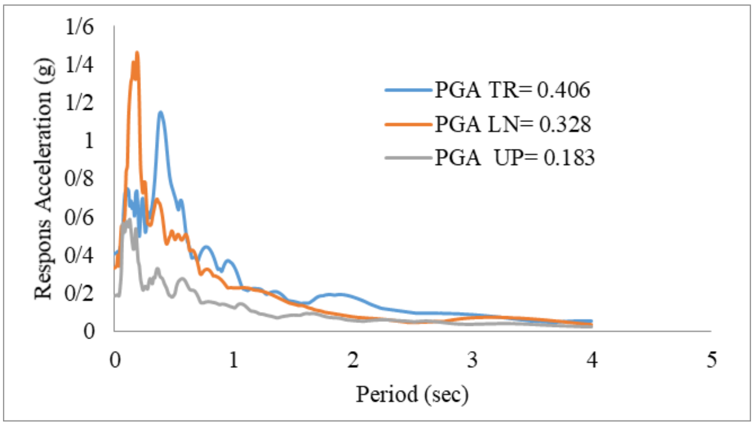


Figure 12. The spectrum of transitional components (including two horizontal orthogonal and vertical components) of the Tabas Earthquake

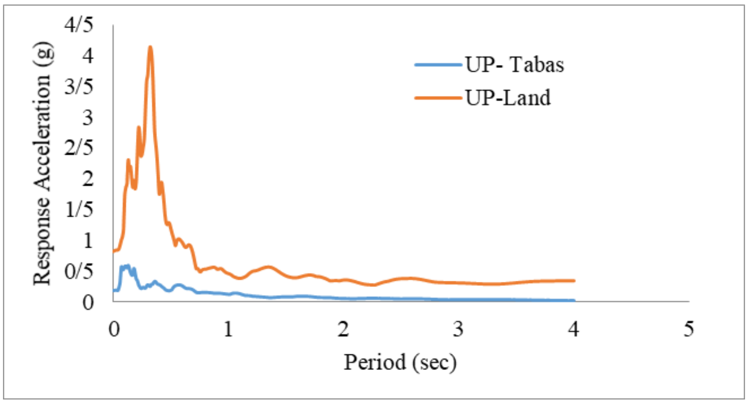


Figure 13. The comparison of vertical spectrums of Tabas and Landers earthquakes

The comparison of the transitional components spectrum of the Tabas and Landers earthquakes indicates that the Landers earthquake spectrum is much stronger than that of Tabas. In particular, the vertical spectrum of the Landers earthquake with PGA equal to 0.818g is much greater than the Tabas earthquake spectrum with PGA of 0.183g, while the recorded magnitude for each earthquake is 7.3 Richter.

The results of the investigation on the spectrums show that even by considering vertical ground motions in the seismic design of the structures without applying the characteristics of sites, the mechanism of seismic springs, the distance from the fault, magnitude, the type of soil, the duration of strong ground motion and its maximum values (PGA, PGV, and PGD), besides depth of bedrock, fault rupture direction in possible earthquakes can not be helpful, and all of these parameters should be considered. PGA of the vertical spectrum of the Landers earthquake is much larger than that of the Tabas earthquake in this research. Furthermore, according to Figs 14 to 19, the duration of strong ground motion in the Landers earthquake is much larger than the same value in the Tabas earthquake. This result reflects the fact that the lack of the appropriate seismic design in earthquakes with a significant vertical component can cause major damage to the structure.

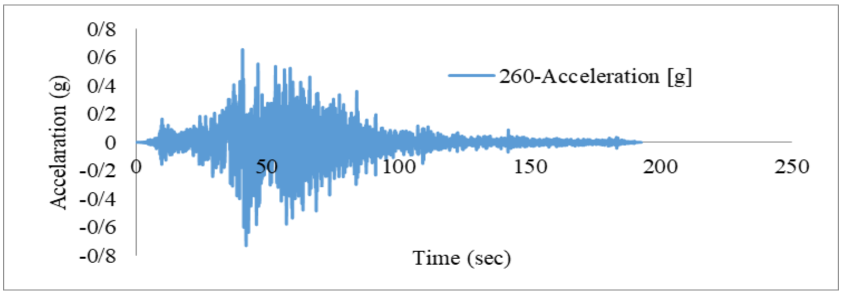


Figure 14. The record of the horizontal component of the Landers earthquake

According to Figs 14 to 19, the records of transitional components of Landers and Tabas earthquakes are investigated, and the PGA values of each record and its related time, besides the duration of strong ground motion, are evaluated.

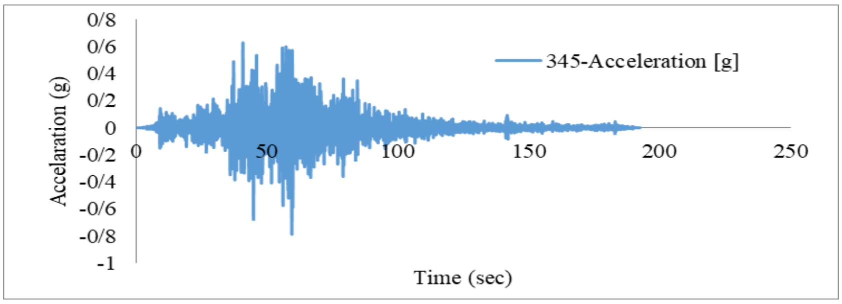


Figure 15. The other record of the horizontal component of the Landers earthquake

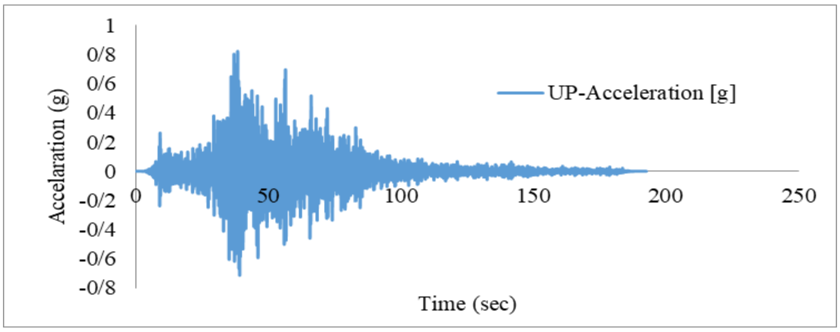


Figure 16. The record of the vertical component of the Landers earthquake

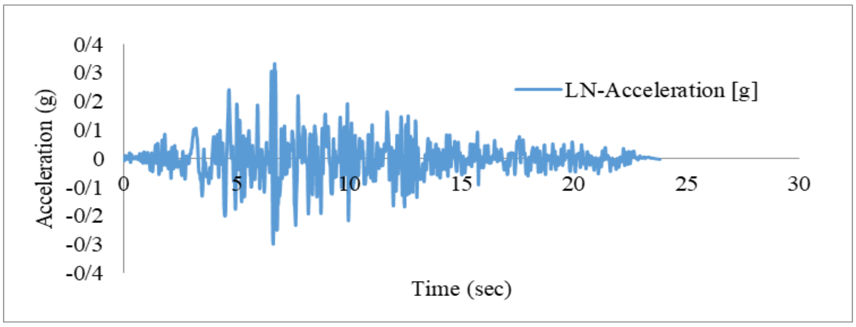


Figure 17. The record of the horizontal component of the Tabas earthquake

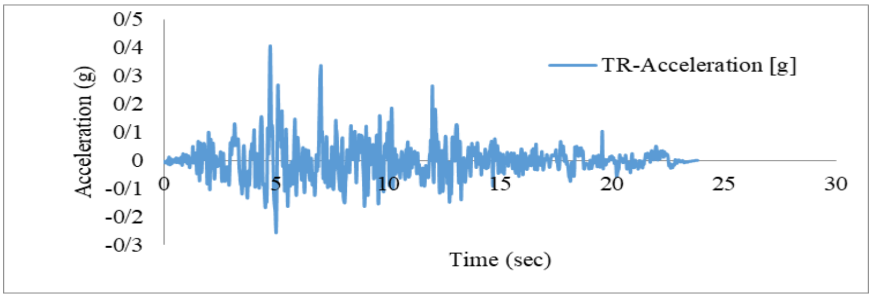


Figure 18. The other record of the horizontal component of the Tabas earthquake

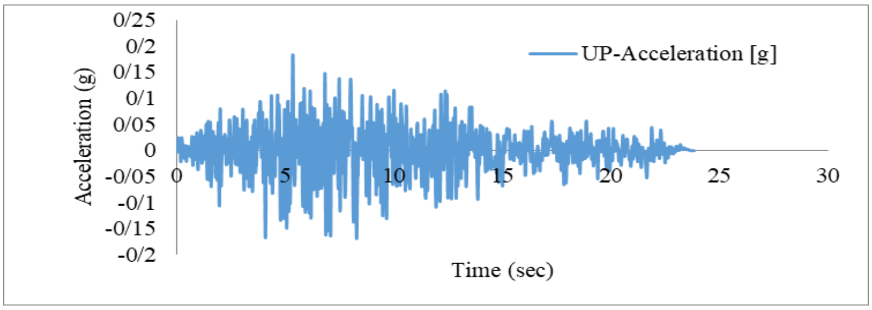


Figure 19. The record of the vertical component of the Tabas earthquake

The comparison of the registered records of the Tabas earthquake indicates that the PGA value of the components of horizontal orthogonal and vertical ground motions are 0.328g, 0.406g, 0.183g, respectively, occurring at the times of 6.7, 4.74, and 5.34 seconds. Also, the examination of the Landers earthquake records shows that PGA of components of horizontal orthogonal and vertical ground motions are 0.727g, 0.789g, and 0.818g, respectively, happening at 41.88, 59.44, and 38.36 seconds. Due to the lack of synchronization of the ground acceleration maximum for horizontal orthogonal components with vertical ground motions and the existence of difference between them, vertical and horizontal components can be applied to the structure separately; this is observed in the fourth edition of the standard No. 2800.

In addition to the above issues, according to Figs. 11 and 12, the inequality of the spectrum of horizontal orthogonal components with that of vertical ground motions of the earthquake is another issue, suggesting that the components of horizontal orthogonal are applied to the structure separately from vertical ground motions to estimate the seismic response of the structures; Otherwise, the estimation of the unrealistic response of structures against the earthquake can be possible.

Surely, the components of horizontal orthogonal and vertical ground motions of the earthquake may be applied to the structures in all cases separately. This is as the results of this research indicate that the vertical ground motions have no significant effect on the base shear of the bridge, and seismic excitations of horizontal orthogonal also have no significant effect on the axial force of the structure in the direction perpendicular to the ground.

The investigation of the actual structure condition before the earthquake shows that the structure is under the influence of gravity loads; the direction of the effect of these loads is in line with the effect of the vertical component of the earthquake. One of the best combinations that can calculate the realistic seismic response of bridges is the application of horizontal orthogonal components to estimate the base shear of the bridge, and the simultaneous application of dead load dynamically and the vertical component of the earthquake on the structure in order to estimate the axial force of the bridge.

Another important parameter in determining the seismic response of structures is considering the duration of strong ground motions and its intensity, as well as the characteristics of near-fault earthquakes in the selection of earthquakes.

6 CONCLUSION

In this study, the studied bridge is modeled in three dimensions to evaluate the effects of the vertical ground motions on the seismic response of RC skewed bridges, and the nonlinear time history analysis and characteristics of Tabas and Landers earthquakes are used to evaluate the studied bridge. Finally, the following results are achieved:

- The application of the vertical ground motions in the seismic design of bridges is essential.
- The application or non-application of vertical ground motions have no significant effect on the amount of base shear of the studied RC skew bridge.
- The application of the vertical ground motions causes a significant increase in the bridge response in its vertical direction than its non-application. For example, it is clear that in the first loading combination, where only the components of horizontal orthogonal of the earthquake are applied to the bridge, the response of the structure is negligible in its vertical direction. On the other hand, in the third loading combination, the vertical axial response of structure against Tabas and Landers earthquakes is 197.4 and 1247 tons, respectively. Besides, it is obvious that in the fourth loading combination, the vertical axial response of the structure against Tabas and landers earthquakes is 2973 and 3339 tons, respectively.
- The vertical displacement of points (A) and (B) at the studied bridge under the influence of the Tabas earthquake is 3.01 and 7.91 cm, respectively, and under the impact of the Landers earthquake is 22.75 and 54.55 cm, respectively. This result indicates that the mere application of the vertical ground motions of the earthquake is not sufficient for seismic design of the bridges, and a complete recognition of the seismic properties of the structure and site has of

particular importance since the intensity of the vertical ground motions can have a significant difference with each other.

- The comparison of the obtained results from the studied structure shows that at least in order to select earthquakes to estimate the seismic response of structures in far regions of the fault, considering the magnitude parameter alone is not sufficient; however, considering the parameters of magnitude, duration of strong ground motion and its intensity, and PGA of earthquakes is very important.
- By studying the records and spectrum of the studied earthquakes, it is found that the spectrums of horizontal orthogonal components with that of vertical ground motions are significantly different, and the spectrum of the vertical component of an earthquake can be much stronger or weaker than that of the horizontal components of the same earthquake. Moreover, the peak time of the vertical component of the earthquake (when PGA occurs) differs from the peak time of the horizontal components; for this reason, the vertical and horizontal components of the earthquake should not be applied to the structures together, but separately.
- The appropriate application of the vertical component of the earthquake than its non-application in the seismic design of the structures causes the structure to function properly against potential earthquakes with significant vertical components and has low seismic vulnerability potentiality.
- The results of the studies indicate that even the simultaneous application of the vertical component of the earthquake and the dead load can not have a significant effect on the base shear of the bridge, and the effect of this loading combination is significant on the structural response in its vertical direction.
- Regarding the realistic conditions of the structure in nature and without conventional idealism, it is clear that the bridges are under the influence of the dead load from their members normally; indeed, during the earthquake, the loads caused by this phenomenon can be added to the dead load. This result suggests that in order to estimate the realistic response of structures in its vertical direction, the simultaneous application of the dead load (dynamically) with the vertical component of the earthquake is essential.
- According to the mentioned items in Iranian codes No. 139 and 463, Third and Fourth Edition of Iranian codes No. 2800, and the Caltrans seismic design criteria (SDC, 2006), regarding the application of the effects of the vertical earthquake component in the seismic design of bridges, and also according to the results of the present study, it is obvious that the mentioned standards are needed to be revised and amended.

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