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Analysis of box-girder bridge Considering Translational and Rotational Components of Earthquake

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ABSTRACT

Due to the importance of bridges as vital arteries and the huge investment of countries in building bridges, the need for more accurate seismic analysis of bridges to better understand their structural behavior is inevitable. Like many structures, the effect of the rotational components of the earthquake on bridges has been less noticed by researchers and designers. This research has evaluated the effect of the rotational components of the earthquake to better understand the seismic behavior of bridge. For this purpose, in addition to three translational components, the rotational components of the earthquake, including two rocking components and one torsional component, have been considered in the three-dimensional seismic analysis of box-girder concrete bridges. By creating the rotational component of the earthquake by the Hong-Nan Li method, three box-girder bridges with pier heights of 12, 30, and 45 meters were subjected to the combined effect of six translational and rotational components, as well as three translational components were separately subjected to under a far-field earthquake with different soil and shear wave velocity. The results of the analysis show that the effect of the earthquake's rotational components on the response of stresses and displacement, depending on the type of earthquake and the characteristics of the bridge structure, can be particularly important.

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1. Introduction

Bridges are the oldest structures and passageways to cross valleys and rivers [1-2]. Also, the continuous expansion of highways worldwide, mainly due to the significant increase in traffic, population, and the extensive growth of urban and metropolitan areas, makes using bridges inevitable. The special impact of the bridge on intracity and suburban communication, as well as the importance of these structures in terms of safety, has forced engineers to design it accurately under earthquake. The occurrence of numerous earthquakes and the damages they cause make a more detailed study of the impact of

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earthquake components on all kinds of structures inevitable.

Many studies have been carried out on all types of structures under the translational components of an earthquake to better understand the performance of structures under an earthquake and also the amount of damage inflicted on them. The earthquake comprises six components, including three translational and three rotational components. The translational components are divided into two horizontal components and one vertical component, and the rotational components are divided into two rocking components (rotation around two horizontal axes) and one torsional component (rotation around the vertical axis). The analysis of structures and bridges under rotational components has been less considered than translational components. For this reason, in this study, bridges with box-girder are examined under the translational and rotational components of the earthquake to determine the impact of rotational components on the response of the behavior of this structure.

Observations made on the rotation of tombstones and chimneys have drawn researchers' attention to the effect of the rotational component of the earthquake [3]. Using theoretical relationships, researchers found two methods to calculate the rotational component. The first method uses the equation of the theory of elasticity, and the second method uses the equation of the theory of elasticity along with the theory of wave propagation. Newmark performed the first method, which provided a simple relationship between the earthquake's translational and rotational components and caused more researchers to investigate this field [4]. Other researchers also used this method after the Newmark study. The methods of calculating the rotational components are diverse; some are divided into direct methods using parallel seismographs, ring lasers, and chemical explosions. Another set uses earthquake translational components based on the elastic theory method and is divided into time derivation, finite difference, and geodetic methods. In this study, we calculate the rotational component using an improved method by Hong Nan Lee, which uses wave propagation theory and elasticity theory [5]. In the Hang Nan Lee method, the wave velocity and the angle of the incident wave are used to calculate the rotational component.

According to the existing methods for calculating the rotational components of the earthquake, various studies have been conducted on different types of structures under rotational components. In 1984, Abdul Ghaffar and Rubin examined the torsional response of the Golden Gate suspension bridge and concluded that this structure's response was necessary for higher mode, and the displacement and cable tensions are under little torsion stimulation, but the flexural stresses are high [6]. Kalani and Navayi Neya studied the effect of spatially varying the rotational and translational components of the earthquake on concrete gravity dams using the Hang Nan Li method. The results of their study express the increasing effect of the rotational component on the instruments' responses. Also, the rotational component impacts the destroyed concrete areas and the crack zone [7]. Kalani et al. investigated the translational and rotational components on the elevated Water Storage Tanks and concluded that the rotational components of ground motion can increase the structure's response, and ground motion analysis with six components can be essential for design control [8]. The results of studies on structures such as cooling towers [9], self-centering base-rocking walls [10], and progressive collapse of steel structures [11] under rotational components of earthquake express the impact of this component on the response of structural behaviour and require consideration of rotational components. The studies of Raghem Moayed [12], Özşahin and Pekcan [13], respectively, on steel girder bridges and skew highway bridges under rotational components, pointed out the increasing effect of rotational components on the response of structures, such as displacement and stress and stated the need to consider the rotational component. Dehmardeh et al.'s study was devoted to examining the effects of the torsional component on the response of buildings and the adequacy of accidental eccentricity, which concluded that the accidental eccentricity to consider Getting the effects of the torsional component is not enough and leads to unreliable responses [14]. The impact of rotational components on the response of structures makes it necessary to investigate this component on bridges. For this purpose, box girder bridges under both the translational and rotational components of the earthquake have been studied in this research.

2. Calculation of earthquake rotational components

According to the six-component analysis, rocking and torsional components will need to be produced because the codes do not mention a direct method for calculating it. For this purpose, this research calculates the rotational components using the Hang Nan Li method [7], which uses the translational component and the theory of elasticity and wave propagation, which is calculated with the help of programming in MATLAB software. Using relationships 1 and 2, respectively, can obtain the time history of rocking and torsional components in which the R domain, θ_w is the frequency phase calculated from the frequency content spectrum w and ω is the angular velocity of the wave, and C_x is the apparent velocity of the waves.

$$\varphi_{gy} = \varphi_{gx} = \frac{i\omega}{C_x} w = e^{\frac{\pi}{2}i} \frac{\omega}{C_x} R_w e^{i\theta_w} = \left(\frac{\omega}{C_x} R_w\right) e^{\left(\frac{\pi}{2}+\theta_w\right)i} \quad (1)$$

$$\varphi_{gz} = \frac{i\omega}{2C_x} v = e^{\frac{\pi}{2}i} \frac{\omega}{2C_x} R_v e^{i\theta_v} = \left(\frac{\omega}{2C_x} R_v\right) e^{\left(\frac{\pi}{2}+\theta_v\right)i} \quad (2)$$

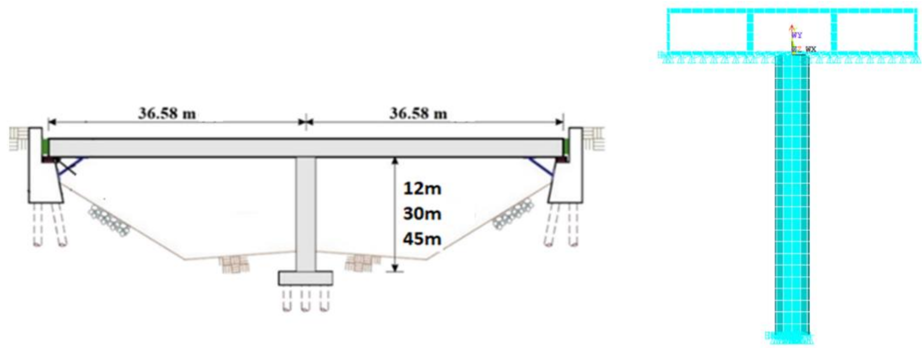

Fig. 1. The geometry of the bridge

3. Numerical modeling of bridges

To investigate the effect of the earthquake's rotational components on bridges, the geometry of the bridge was selected from a reference [15], and it is shown in Figure 1. The examined concrete box-girder bridge is 73.16 meters long, has a pier height of 12 meters, and a deck width of 10.75 meters. To thoroughly investigate the behavior of the bridge under the rotational components of the earthquake and compare it with the translational components, two other bridges were modeled by increasing the pier height to 30 and 45 meters. Table 1 presents the geometry of the bridges, and Table 2 provides the specifications of the materials used.

Table 1.
Geometrical characteristics of the investigated bridge per meter unit

Model	Pier height	Pier diameter
1	12	1.52
2	30	2.5
3	45	3.00

Table 2.
Specifications of the investigated bridge materials

Type of material	Modulus of elasticity (GPa)	Density (kg/m^3)	Poisson's ratio
Concrete	27.2	2400	0.2
Steel	20	7850	0.25

Soil structure interaction was not considered, and the bridge pier was considered restrained. Also, due to the presence of a shear key in the abutment to prevent the transversal movement of the bridge, the abutment is restricted in the transverse direction in addition to vertical movement.

For the analysis and modeling of the three-dimensional bridges examined, Ansys finite element software and Solid 65 element, including eight nodes, each node containing three degrees of translational freedom, have been used. The Solid 65 element can model reinforced concrete and defined as a percentage of the volume ratio, in this study, the reinforcement for the pier height is 13%, and for the deck, it is considered a value of 2%.

4. Earthquake records

The selection of earthquake records is an essential part of the seismic analysis that will be effective in obtaining results. For this research, three earthquake records for soil type 3 and three earthquake records for soil type 2 were selected according to the standard 2800, and the characteristics of the records are given in Tables 3 and 4.

Table 3.
Characteristics of earthquake recording, soil type 3

Earthquake	Station	Magnitude (Richter)	Rjb (km)	Vs30 (m/sec)
Kobe	HIK	6.9	95.72	256
Northridge	LA – W 70th St	5.28	30.46	241.41
Taiwan SMART1	SMART1 M01	6.5	96.28	268.37

Table 4.
Characteristics of earthquake recording, soil type 2

Earthquake	Station	Magnitude (Richter)	Rjb (km)	Vs30 (m/sec)
Tabas	Bajestan	7.35	119.77	377.56
Northridge	Lake Hughes #4 – Camp Mend	6.69	31.27	600.06
Taiwan SMART1	Fort Tejon	6.61	59.52	394.18

5. Numerical analysis

In order to ensure the correctness of numerical modeling, first, sensitivity analysis is done to determine the proper dimensions of the element and then the validity of the bridge model.

5.1. sensitivity analysis

To perform the sensitivity analysis, we have to reduce the size of the elements in several steps so that the results are independent of the element size. To determine the dimensions of the element, the displacement sensitivity analysis of the middle of the bridge span in the vertical direction (U_y) was performed under static analysis by changing the dimensions of the element and calculating the displacement at each step. In Figure 2, the displacement is shown by changing the size of the element. According to Figure 2, the sensitivity analysis is considered for the element to dimensions from 1.5 meter to 0.25 meter, and according to the time required to analyze, the bridge models have been selected to 0.5 meters element. Then, the number of bridge elements with 12, 30, and 45 meters pier heights is 21030, 21890, and 23712, respectively.

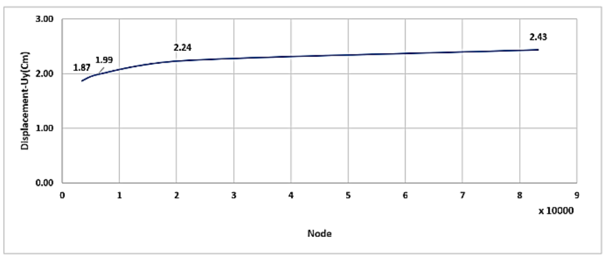

Fig. 2. The displacement sensitivity analysis of the middle of the bridge span with a 12-meter pier height.

6. Validation of the bridge

To verify the bridge model in the Ansys software, the period of the bridge in the reference [13] and the model carried out in this research will be compared. The period is one of the critical indicators that influence the analysis and response of structures, and a slight change in the period of structures will cause differences in the results and responses of the analyses. For this purpose, according to Table 5, it is observed that the difference in the period of reference 13, which was modeled and analyzed with the OpenSees, and the bridge modeling done in this study was very small; it is possible to understand the accuracy of modeling as well as the results of the analysis. In addition to this, the vertical reaction in the supports and its equality with the weight is another proof of the accuracy of the modeling of the present research.

It is noteworthy that for soil type 2, Northridge, San Fernando, and Tabas earthquakes are considered, and the bridge with three different pier heights of 12, 30, and 45 meters have been analyzed, which, due to the limited number of pages, is excluded from its presentation.

Table 5.
Validation of the bridge's period

The Finite Element Model	Period (sec)
Reference [15]	1.29
Ansys model	1.2977

7. Results

Three series of bridges with pier heights of 12, 30, and 45 meters were subjected to the combined effect of six translational and rotational components, as well as three translational components were separately subjected to a far-field earthquake with different soil and shear wave velocity. To compare the results of the time history analysis, the displacements Ux, Uy, and Uz, which are respectively in the transverse, vertical, and longitudinal directions of the bridge, are presented in centimeters, and the principal stresses (S1, S2, S3) are offered in kilopascals. Figures 3 and 4, respectively, show the time history of the displacements and points A, B, and C, and the principal stresses for point B are for the analysis of six and three components of the Northridge earthquake of soil type 3 for a bridge with a pier height of 12 meters. Also, tables 6 to 8 summarize results from other analyses for displacements and principal stresses for bridges 12, 30, and 45(m) of soil type 3.

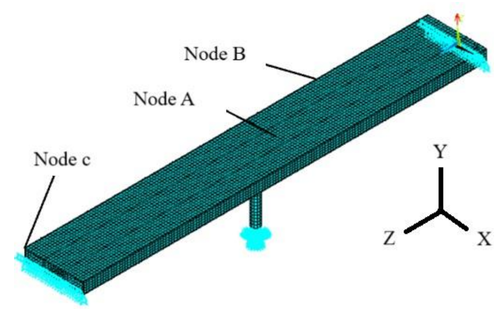

Fig. 3. Maximum points of displacement and stress of the bridge with 12(m) pier height

8. Conclusion

According to the analysis of bridges with different heights and earthquakes, the impact of rotational components on the box bridge is as follows:

- Among the results of the analyses carried out under three and six components of the type 3 soil earthquake, the effect of the rotation component of the Northridge earthquake was more effective and had an increasing impact on the results of the displacements and stresses created in the bridges. As a result of the increase in the pier height, the percentage of the difference between three and six components in stress and displacements increased, which is the result of the effect of the rotational component.

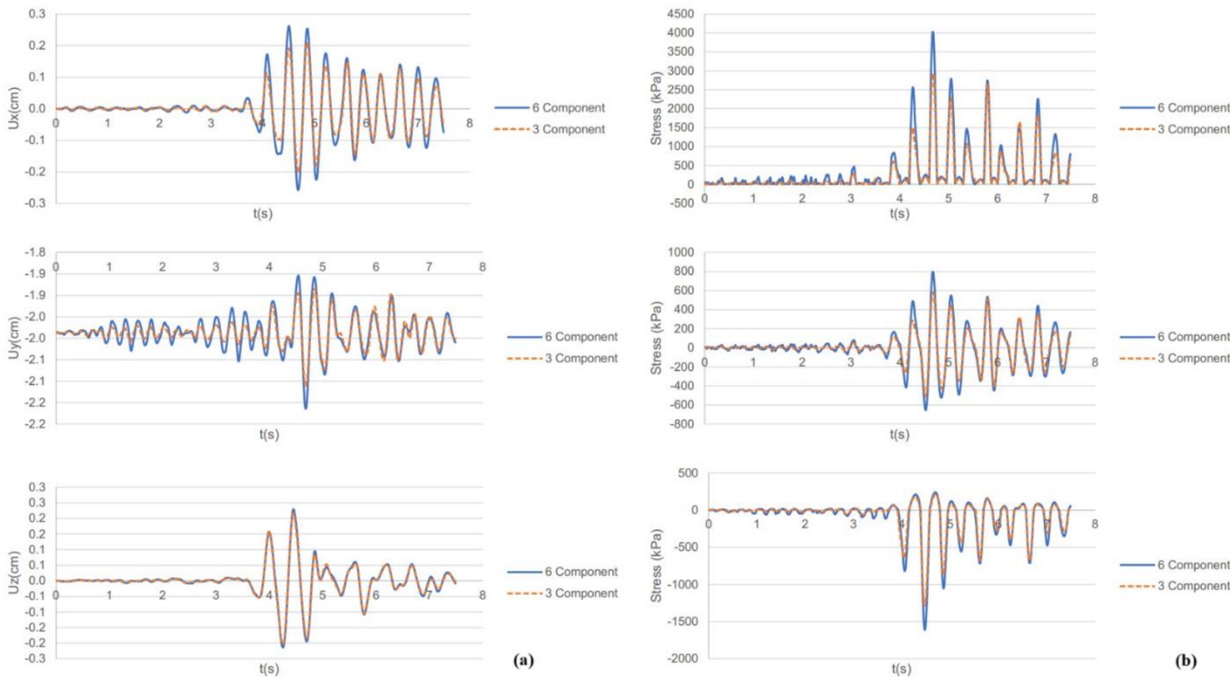

Fig. 4. Time history analysis, a) displacement b) principal stress

Table 6.

Results of bridge analysis with a pier height of 12(m) under soil type 3 earthquake

Maximum Displacement(cm)	**Three-component**			**six-component**		
	Kobe	Taiwan SMART1	Northridge	Kobe	Taiwan SMART1	Northridge
Transverse direction (Ux)	1.13	0.227	0.209	0.896	0.242	0.263
Vertical direction (Uy)	-1.41	-2.144	-2.112	-1.453	-2.205	-2.165
longitudinal direction (Uz)	3.96	1.97	0.217	3.96	1.97	0.23
Principal stresses (kPa)	**Three-component**			**six-component**		
	Kobe	Taiwan SMART1	Northridge	Kobe	Taiwan SMART1	Northridge
S1	18823.5	10575.3	2933.7	18842.6	10553.4	4008.5
S2	2174.9	-2637.13	580.2	2173.7	-2616.14	795.4
S3	-20476.6	-11747	-1284.2	-20469.3	-11750.9	-1610.06

- The maximum increase in displacement values for soil type 3 in the analysis of six components compared to the three components of the bridge with pier heights of 12, 30, and 45 meters is 20.53%, 61.92%, and 39.85%, respectively. And for soil type 2, these values are 13.73%, 14.5% and 19%, respectively.
- The maximum increase of the maximum stress values for soil type 3 in the analysis of six components compared to three components for the bridge with pier height of 12, 30, and 45 meters is 26.8%, 67.3%, and 47.8%,

respectively. And for soil type 2, these values are 20.5%, 26.87% and 48.84%, respectively.

- In the six-component analysis, the rotational component does not always have an increasing effect, and like the soil type 3 Kobe earthquake, it has a decreasing effect on the stress values and displacements. However, in the vertical axis (Y), due to the rotation component that rotates around this axis, the incremental effect of the rotational component is evident in three bridge models. The increase or decrease of the response of the six-component analysis can also be attributed to the frequency spectrum of the earthquake.

Table 7.
Results of bridge analysis with a pier height of 30(m) under soil type 3 earthquake

Maximum Displacement(cm)	Three-component			six-component		
	Kobe	Taiwan SMART1	Northridge	Kobe	Taiwan SMART1	Northridge
Transverse direction (Ux)	-1.477	-0.297	-0.286	-0.98	-0.297	0.751
Vertical direction (Uy)	-2.171	-1.676	-1.894	-2.29	-1.672	-2.06
longitudinal direction (Uz)	-3.147	2.08	0.203	-3.136	2.129	-0.291
Principal stresses (kPa)	**Three-component**			**six-component**		
	Kobe	Taiwan SMART1	Northridge	Kobe	Taiwan SMART1	Northridge
S1	12061	2050.93	2375.1	8126.2	2422.25	7255.6
S2	2455.8	-487.7	494.8	-1782.6	-482.1	1376.2
S3	-3023.9	-428.7	-391.8	-2378.4	-425.3	-1165.85

Table 8.
Results of bridge analysis with a pier height of 45(m) under soil type 3 earthquake

Maximum Displacement(cm)	Three-component			six-component		
	Kobe	Taiwan SMART1	Northridge	Kobe	Taiwan SMART1	Northridge
Transverse direction (Ux)	-2.133	0.576	-0.335	1.846	0.636	-0.557
Vertical direction (Uy)	-1.408	-1.66	-1.763	-1.541	-1.657	-1.926
longitudinal direction (Uz)	3.08	-1.843	0.19	3.134	-1.873	0.2
Principal stresses (kPa)	**Three-component**			**six-component**		
	Kobe	Taiwan SMART1	Northridge	Kobe	Taiwan SMART1	Northridge
S1	4726.9	2251	953.8	5825.6	2457.1	1827.2
S2	-2064	811.2	291.4	-19442.2	846.2	548.2
S3	-6325.4	-1642.5	-940.5	-4838.5	-1487.3	-1736

- In soil type 2 earthquakes, the difference between the results of three and six earthquake components has increased, which can also be pointed to the effect of the rotational component in soil type 2. Also, compared to the analysis of soil type 3 earthquakes, the reduction effect caused by the rotational component is much less.

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