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The effects of vertical earthquake motion on an R/C structure

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Abstract. The present study investigated the earthquake behavior of R/C structures considering the vertical earthquake motion with the help of a comparative study. For this aim, the linear time-history analyses of a high-rise R/C structure designed according to TSC-2007 requirements were conducted including and excluding the vertical earthquake motion. Earthquake records used in the analyses were selected based on the ratio of vertical peak acceleration to horizontal peak acceleration (V/H). The frequency-domain analyses of the earthquake records were also performed to compare the dominant frequency of the records with that of the structure. Based on the results obtained from the time-history analyses under the earthquake loading with (H+V) and without the vertical earthquake motion (H), the value of the overturning moment and the top-story vertical displacement were found to relatively increase when considering the vertical earthquake motion. The base shear force was also affected by this motion; however, its increase was lower compared to the overturning moment and the top-story vertical displacement. The other two parameters, the top-story lateral displacement and the top-story rotation angle, barely changed under H and H+V loading cases. Modal damping ratios and their variations in horizontal and vertical directions were also estimated using response acceleration records. No significant change in the horizontal damping ratio was observed whereas the vertical modal damping ratio noticeably increased under H+V loading. The results obtained from this study indicate that the desired structural earthquake performance cannot be provided under H+V loading due to the excessive increase in the overturning moment, and that the vertical damping ratio should be estimated considering the vertical earthquake motion.

Keywords: vertical earthquake motion; V/H ratio; modal damping; R/C structure; overturning moment; vertical displacement

1. Introduction

Earthquakes force civil engineering structures in three dimensions, namely two orthogonal horizontal dimensions and the vertical dimension. Structural systems possess high resistance to earthquake motion in horizontal direction. Vertical component was generally not considered in the earthquake analysis of structures (Elnashai and Di Sarno 2008). Besides, many earthquake codes

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(NBC105 1994, UBC 1997, Eurocode-8 1998, IS: 1893 2000, NZS1170.5 2004, ASCE 2007, TSC 2007, ASCE 2010, ASCE 2014, PEER 2015) have taken this motion into account in design. Therefore, many investigations on the vertical earthquake motion have been made by researchers of earthquake and structural engineering. In various earthquakes in the last decades, such as Loma Prieta (1989), Northridge (1994), Kobe (1995), L'Aquila (2009) and NZ sequences (2010, 2011), shear and compressive/tensile failures resulted in brittle behavior of numerous structures. This brittle behavior was observed especially in earthquakes whose vertical component is more dominant than horizontal component.

The main reasons for ignoring the vertical component in design and analysis are generally based on the following assumptions;

• Vertical earthquake component attenuates faster than the horizontal earthquake component.
• Structures are well-designed to vertical loadings.

The considerations have been valid for far-fault earthquakes; however, for near-fault earthquakes the vertical component has considerable significance on seismic behavior of structures. Especially for earthquakes whose ratio of vertical to horizontal acceleration is higher than 1.0, the vertical earthquake motion is directly utilized. In structural analysis, the highest peak acceleration of vertical ground motion is considered to be two-third of the respective value of the horizontal ground motion. Another approach for taking the effect of the vertical earthquake motion into account is to propose additional design provisions. For example, the Turkish Seismic Code (TSC 2007) recommends certain limitations to the vertical irregularities and additional reinforcement arrangements in structural elements.

For vertical ground motions, Elgamal and He (2004) carried out a comprehensive review study. From data analysis of a total of 111 strong ground motions including far-field and near-field records, they showed that far-field records were more effective at lower frequencies than near-field records with energy at higher frequencies. Concerning the vertical earthquake behavior of R/C structures, a limited number of studies were conducted aftermath site observations of the recent destructive earthquakes. Pioneering study including field and analytical evidences was conducted by (Papazoglou and Elnashai 1996). They proved that some failure modes were directly pertinent to the vertical earthquake motion. Also, it was concluded that the vertical earthquake motion gave rise to reducing shear and flexure resistance due to direct tension. In that study, the relationship between the first horizontal mode and the vertical mode for both R/C and steel buildings were presented. In an attempt to calculate the vertical earthquake motion, Elnashai and Papazoglou (1997) proposed acceleration spectra having bilinear inelastic features. With the help of the spectra, modal analysis might be conducted to predict the vertical seismic action on buildings. Depending on magnitude, source-distance and site geology, Ambraseys and Simpson (1996) presented equations for the estimation of vertical acceleration spectrum. Using the equations developed for European earthquake record data set, the ratio of vertical to horizontal peak spectral acceleration (V/H) was determined to be between ½ and ¼. Bozorgnia and Campbell (2004) developed a simplified procedure for the vertical design spectrum using a number of near-field earthquake records. They also proposed a model for estimating the V/H spectra, and indicated that these spectra could be taken into account for earthquake analysis of structures. Related to combining the vertical and horizontal earthquake motions, a simple procedure was recommended by (Collier and Elnashai 2001). The main advantage of this procedure was to easily estimate the effect of the vertical earthquake motion on seismic behavior of structures. They indicated that considering vertical ground motion in analysis was necessary for structures built within 25 km radius of earthquake source, and that V/H>1.0 was acceptable within 5.0 km of earthquake source while this ratio could be considered as 2/3 within 25 km of earthquake source. Using the strong ground motions recorded during Northridge Earthquake, Bozorgnia *et al*. (1998) investigated the vertical response of twelve instrumented structures. The study concluded that the structures were subjected to considerable vertical spectral acceleration depending on their identified vertical dynamic characteristics. Ambraseys and Douglas (2003) conducted a fundamental study to understand the effect of the vertical earthquake motion on horizontal behavior of structures. For this aim, they used a set of single-degree-of-freedom systems (SDOF) and 186 near-field earthquake records. It was concluded that the vertical seismic action might be ignored.

Among recently investigated studies in literature, Reyes and Kalkan (2011) carried out a study on the effect of the vertical earthquake ground motion for a horizontally skewed and curved bridge. They demonstrated that considering this motion in analysis and design might increase the seismic safety level of bridges particularly located at moderate-to-high seismic zone. The influence of the vertical earthquake motion on the seismic behavior and fragility of highway bridges was investigated by Jeon *et al.* (2015). Rather than the shear model with constant axial force, the shear model with varying axial force resulting from the vertical earthquake motion had noticeable effect on the increase in the probability of damage level of the bridge. Lee and Mosalam (2014) conducted a study that includes vertical excitation on shear capacity of the bridge column. Based on the results of analytical and code evaluation as well as experimental tests, the most important finding of the study was that considerable increase in tensile strain due to vertical excitation gave rise to shear failure of reinforced concrete bridge column. A comprehensive experimental investigation on the effect of the vertical earthquake motion on R/C bridge pier was made by Kim (2011). They showed that the presence of the vertical earthquake motion might significantly affected the response of R/C bridge pier and failure mode. Ghaffarzadeh and Nazeri (2015) studied the horizontal behavior of structures subjected to the vertical earthquake motion. It was concluded that horizontal spectral displacement increased significantly in certain vibration periods of structure depending on the increase in the V/H ratio. Similar results were obtained by Kim and Kim (2013). They indicated that structures built in near fault zone leading to higher V/H ratio should be analyzed and designed considering vertical ground motion. In addition to the papers, most pertinent studies on vertical response of buildings and bridges were carried out by (Kim 2008, Kim and Elnashai 2008, Piolatto 2009, Shrestha 2009, Kadid *et al*. 2010, Di Sarno *et al*. 2011, Kim *et al*. 2011, Dana 2014, Wang *et al*. 2015).

2. Earthquake ground motion records

The vertical component of earthquakes has high frequency content (corresponding low period) since it is related to P-waves with lower wavelength than S-wave. Besides, the arrival time of P-waves is relatively shorter than S-waves, which means that structures are firstly excited in vertical direction. In case that vertical dynamic period of structures is close to dominant period of the vertical earthquake motion, structural actions in vertical directions considerably increase. Many seismic codes (TSC 2007, ASCE 2010, Reyes and Kalkan 2011) recommends to be used at least 3 and 7 earthquake ground motions for the time-history analysis depending on the some restrictions: (i) maximum value should be considered if used 3 earthquakes and (i) the average value of all earthquakes should be used if used 7 earthquakes. Considering near-field criterion, Imperial Valley (1979), Kobe (1995) and Kocaeli (1999) earthquake records obtained from (PEER 2015) database were selected to carry out the linear time-history analysis. According to specifications for selection

Table 1 General properties of the earthquake records

Year	Earthquake	Station	PGA (g)			Time (sec)	V/H
			H_1	H_2	V		
1979	Imperial Valley	El Centro Array #6	0.45	0.44	1.90	39.08	4.31
1995	Kobe	Port Island	0.35	0.29	0.57	41.98	1.96
1999	Kocaeli	Gebze	0.26	0.14	0.19	27.99	0.73

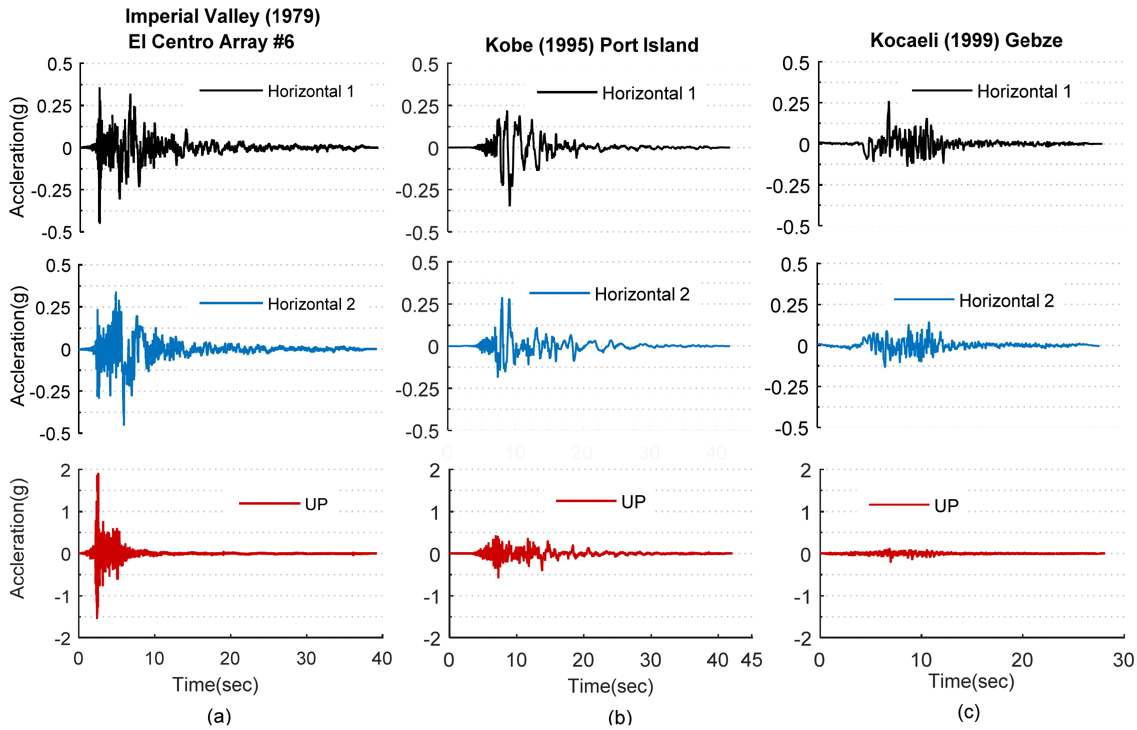


Fig. 1 Earthquake records

of the number of earthquake, maximum and minimum results were given in this study. General properties of the records are given in Table 1. In this table, the vertical to horizontal ratio of the records ranges from high to low. These records were used for a better understanding of the V/H effects on vertical response of structures. All records are also shown in Fig. 1.

As shown in Fig. 2, the vertical and horizontal components of the earthquake records were also processed in the frequency-domain to determine their dominant modal frequencies. Moreover, Arias intensity of the earthquakes is given to prove considerable effect the vertical component on structure. In Fig. 2, Imperial Valley (1979) can be seen to have a higher frequency than the other two earthquakes, which means that it is relatively effective in short period range. Fourier spectrums also indicated that energy of the vertical components concentrated a narrow high frequency band compared to that of the horizontal components. As the V/H ratio decreases from high to low in Table 1, the frequency content of the vertical components is getting closer to that of the horizontal components. From such trend in the frequency-domain, it can be seen that the V/H ratio has significant effect on frequency content. This conclusion was based on the data from three

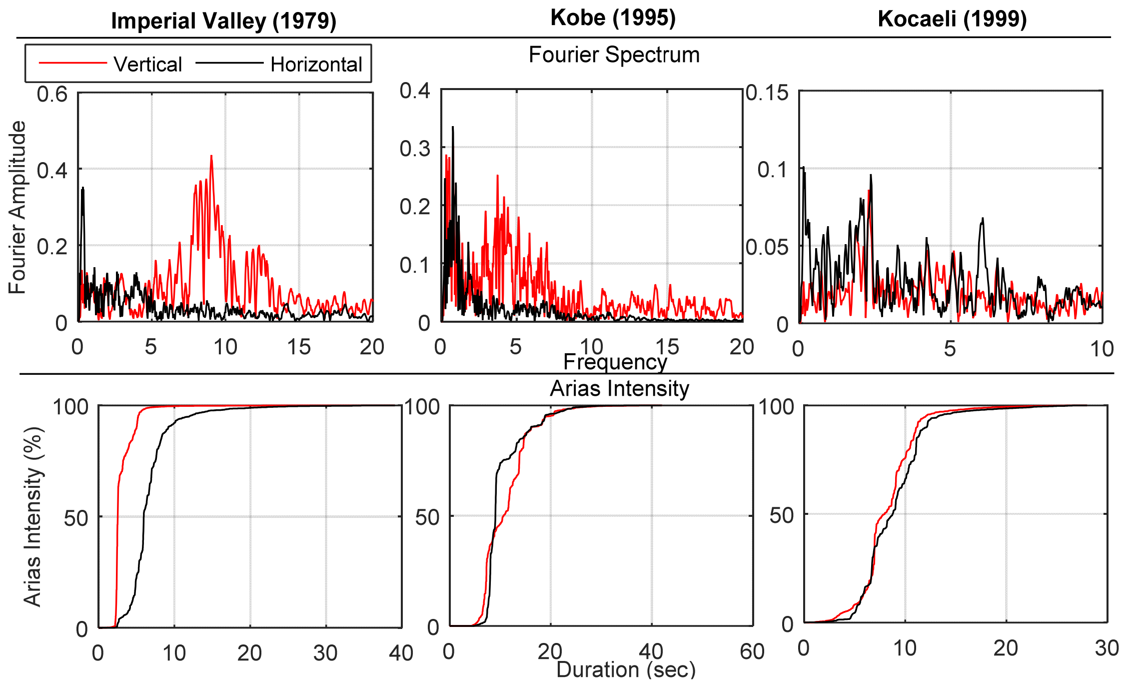


Fig. 2 Analysis of the vertical components of the earthquakes

earthquakes. A larger number of earthquake motion dataset will be useful to derive a more general conclusion. The dominant frequencies of the vertical components were determined as 9.03 s^{-1}, 3.75 s^{-1} and 2.30 s^{-1} respectively for Imperial Valley (1979), Kobe (1995), Kocaeli (1999). The findings from data processing will be associated with the results obtained from modal analysis of the structure to identify the vertical earthquake motion effect on the structure.

3. Numerical model and dynamic analysis of the structure

3.1 Properties of the structure

The structure to be considered in the time-history analysis is an existing high-rise R/C building. The R/C building was designed in compliance with the requirements of the Turkish Seismic Code (TSC 2007). The foundation system of the structure is mat foundation, and the structure has same floor plan in each story. The structural system of the building is shear wall-frame system (semi-ductile frame). The floor plan of the structure is shown in Fig. 3, and all other details are presented in Table 2. From Fig. 3, the structure has no irregularity due to the absence of any cantilever elements and symmetric position of the vertical-bearing elements.

3.2 Numerical model

Based on the project specifications, 3-D finite element-FE model of the structure was developed through (SAP2000 2015). In the model, all beams and columns as well as shear walls

Table 2 Properties of the structure

Number of story	10
Height of story (m)	4.5
Occupation type	Municipality
Structural system	Shear wall-frame (*R*=7)
Concrete class	C35 (f_{ck}=30 MPa)
Reinforcement class	S420 (f_{yk}=420 MPa)
Live load participation factor, *n*	0.3
Seismic zone	1^{st} (A_0=0.4)
Importance factor (I)	1.5
Local site class	Z3, (T_a=0.15 s, T_b=0.60 s)

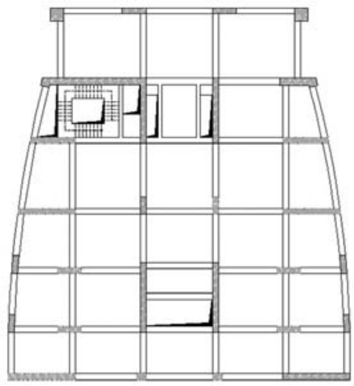


Fig. 3 Floor plan

were modeled as frame elements whereas shell elements were used for the concrete slab. The foundation was not incorporated to the structural model for two reasons. First, the structure had a mad foundation, which is extremely rigid. Secondly, the ground floor of the structure was completely surrounded by shear-walls. These two reasons cause the boundary conditions at the base of the structure to be quite close to the fixed conditions. Therefore, there was no need for including the foundation to the model. Assigning different rigid diaphragm for each story, concrete slab is provided to transmit seismic load, safely. Moreover, the column and beam elements were modeled in a way to account for nonlinear behavior. For this objective, the concentrated plastic strain assumption, called plastic hinge, was considered for the two ends of each element. Numerical model of the structure is shown in Fig. 4.

3.3 Modal analysis

After modeling the structure, the first attempt is to obtain its dynamic characteristics so as to compare the vertical dominant frequency of the structure with that of the vertical earthquake motion from the earthquake records. As shown in Fig. 5(a), the fundamental period and corresponding mode shape were determined in lateral direction with a frequency value of 1.41 s^{-1}. The vertical dominant frequency of the structure is 10.84 s^{-1}, and the associated mode shape is

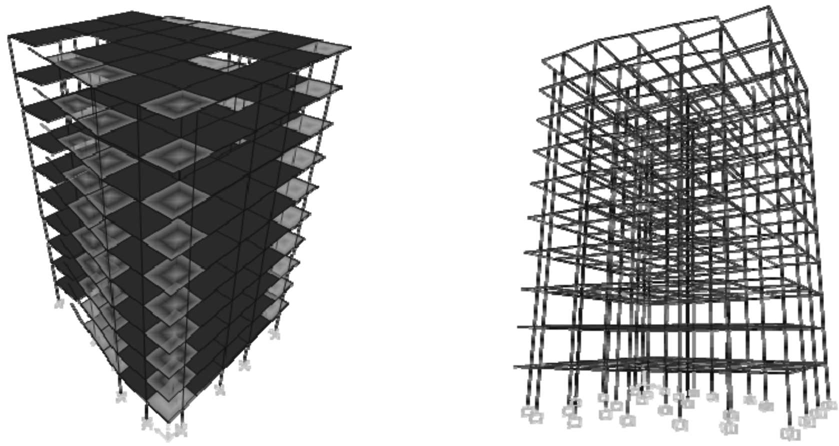


Fig. 4 3-D Finite element model of the structure

(a) Lateral (b) Vertical

Fig. 5 Modal periods and associated mode shapes

demonstrated in Fig. 5(b).

The fundamental frequency of the structure in vertical direction (10.84 s^{-1}) is relatively close to dominant frequency (9.03 s^{-1}) of the vertical component of Imperial Valley (1979) rather than the other two earthquakes (3.75 s^{-1} and 2.30 s^{-1}). Depending on these outcomes, it is expected from the linear time-history analysis that Imperial Valley (1979) has greater effects on the structure than the others, and that Arias intensity is higher than the others as given in Fig. 2.

4. Time-history analysis of the structure

The linear time-history analysis was conducted to determine the fundamental structural parameters including the base shear force, the overturning moment, the top-story lateral displacement, the top-story vertical displacement and the top-story rotation angle. In all time-history analyses, P-Delta effect was also considered. For this aim, the R/C structure was simultaneously excited by two horizontal components of the records (H), and then the analysis was repeated considering the vertical components (H+V). The results obtained from two analyses

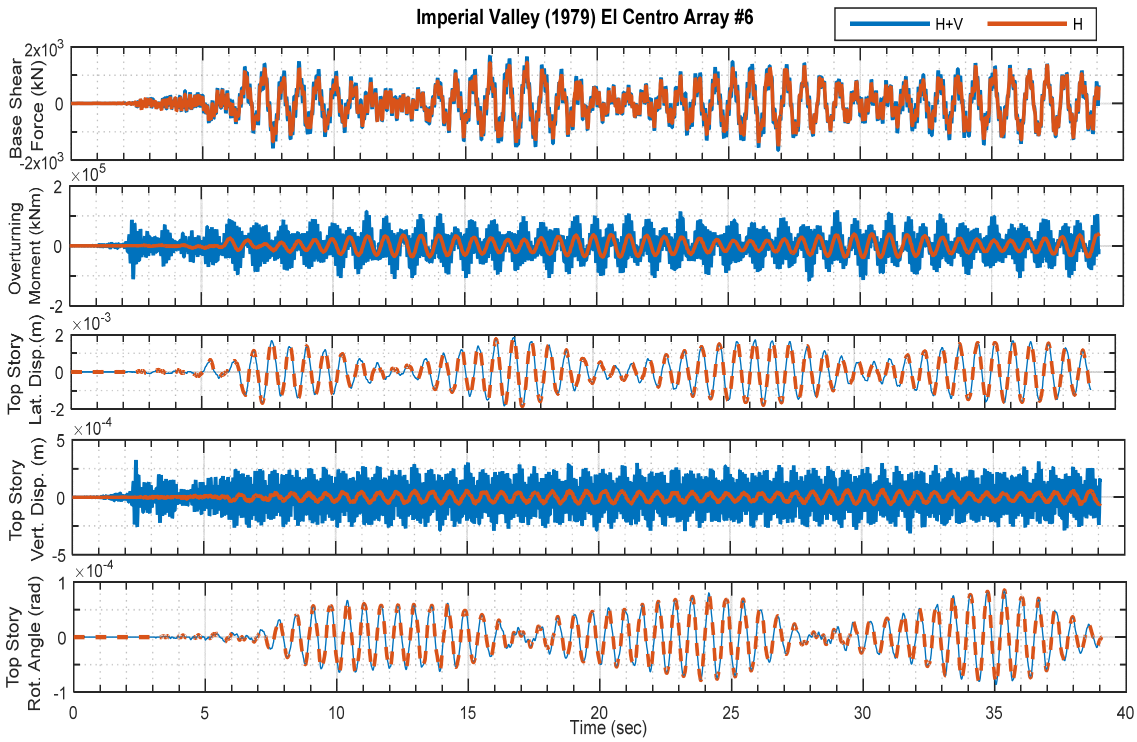


Fig. 6 Analysis results from Imperial Valley (1979)

Table 3 The results from Imperial Valley (1979)

Imperial Valley (1979) El Centro Array#6						
Structural Parameter		Horizontal (H)	Horizontal + Vertical (H+V)	Difference (H+V)-(H)	Variation (%)
Base Shear Force (kN)	Max.	1.458×10^3	1.681×10^3	2.23×10^2	15.27
	Min.	-1.493×10^3	-1.656×10^3	-1.63×10^3	10.90
Overturning Moment (kNm)	Max.	39.758×10^3	118.360×10^3	78.602×10^3	197.70
	Min.	-39.864×10^3	-116.720×10^3	-76.856×10^3	192.80
Top Story Vertical Displacement (m)	Max.	6.9×10^{-5}	32.6×10^{-5}	26×10^{-5}	370.52
	Min.	-6.5×10^{-5}	-31.5×10^{-5}	-25×10^{-5}	384.59

provided opportunity to quantify the effect of the vertical earthquake motion on the R/C structure.

Fig. 6 shows the results obtained from the linear time-history analysis of Imperial Valley (1979). The base shear force had the same trends for H and H+V loading conditions during the earthquake. Similar variation was obtained for the top-story lateral displacement and the top-story rotation angle. This means that the vertical earthquake excitation has no considerable effect on these structural parameters.

When it comes to the overturning moment and the top-story vertical displacement variation, the vertical earthquake excitation relatively amplified these structural parameters. The results from the base shear force, the overturning moment and the top-story vertical displacement are given in

Table 3.

The overturning moment and the top-story vertical displacement increased by 200% and 400%, respectively. Noticeable increase in the overturning moment can lead to increase in damage level of structural elements of the structure, which means that performance level of the structure cannot be provided upon considering the vertical earthquake motion. Due to almost 400% increase in the vertical displacement, out of plane translation can be observed in R/C slab. This type of behavior causes the slab not to transmit seismic load to the columns properly.

As shown in Figs. 7-8 for Kobe (1995), Kocaeli (1999), the variation of the structural

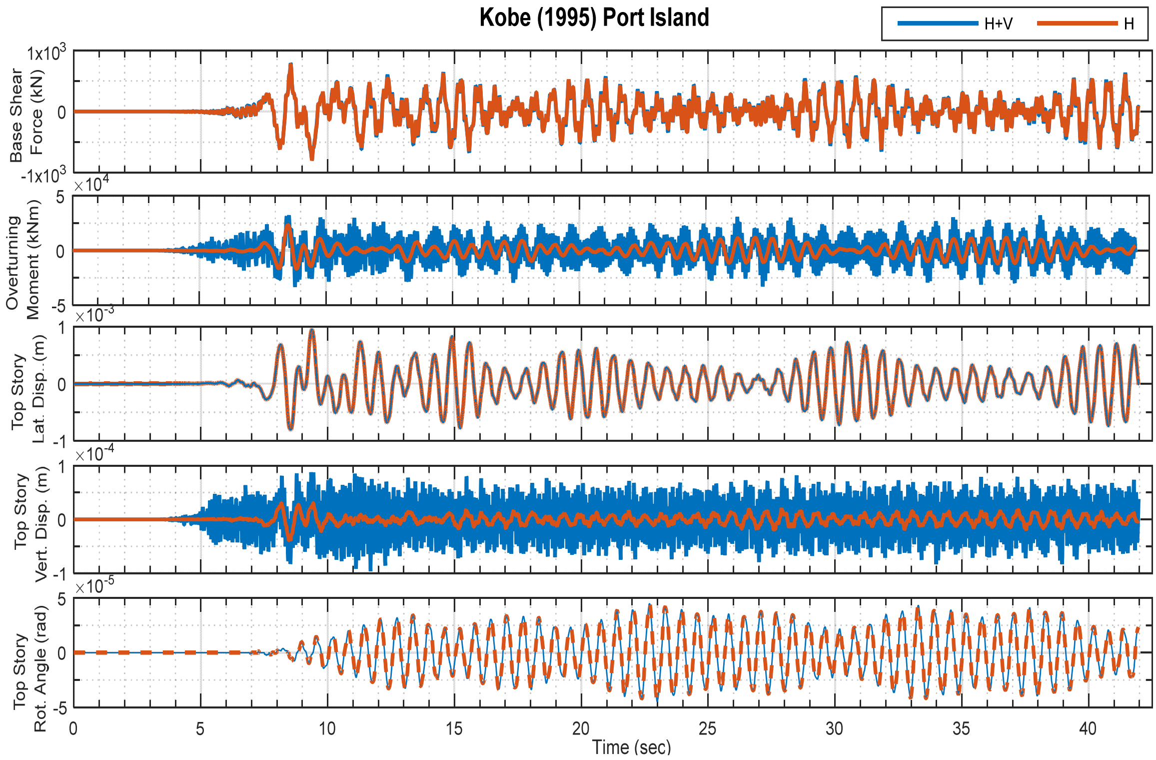


Fig. 7 Analysis results from Kobe (1995)

Table 4 The results from Kobe (1995)

Kobe (1995) Port Island						
Structural Parameter		Horizontal (H)	Horizontal + Vertical (H+V)	Difference (H+V)-(H)	Variation (%)
Base Shear Force (kN)	Max.	7.68×10^{2}	7.87	19.24	2.50
	Min.	-7.80×10^{2}	-7.87	12.64	-1.58
Overturning Moment (kNm)	Max.	23.387×10^{3}	32.253×10^{3}	8.866×10^{3}	37.91
	Min.	-16.878×10^{3}	-33.440×10^{3}	-16.562×10^{3}	98.13
Top Story Vertical Displacement (m)	Max.	3.1×10^{-5}	8.8×10^{-5}	6.0×10^{-5}	183.23
	Min.	-3.9×10^{-5}	-9.7×10^{-5}	-6.0×10^{-5}	147.69

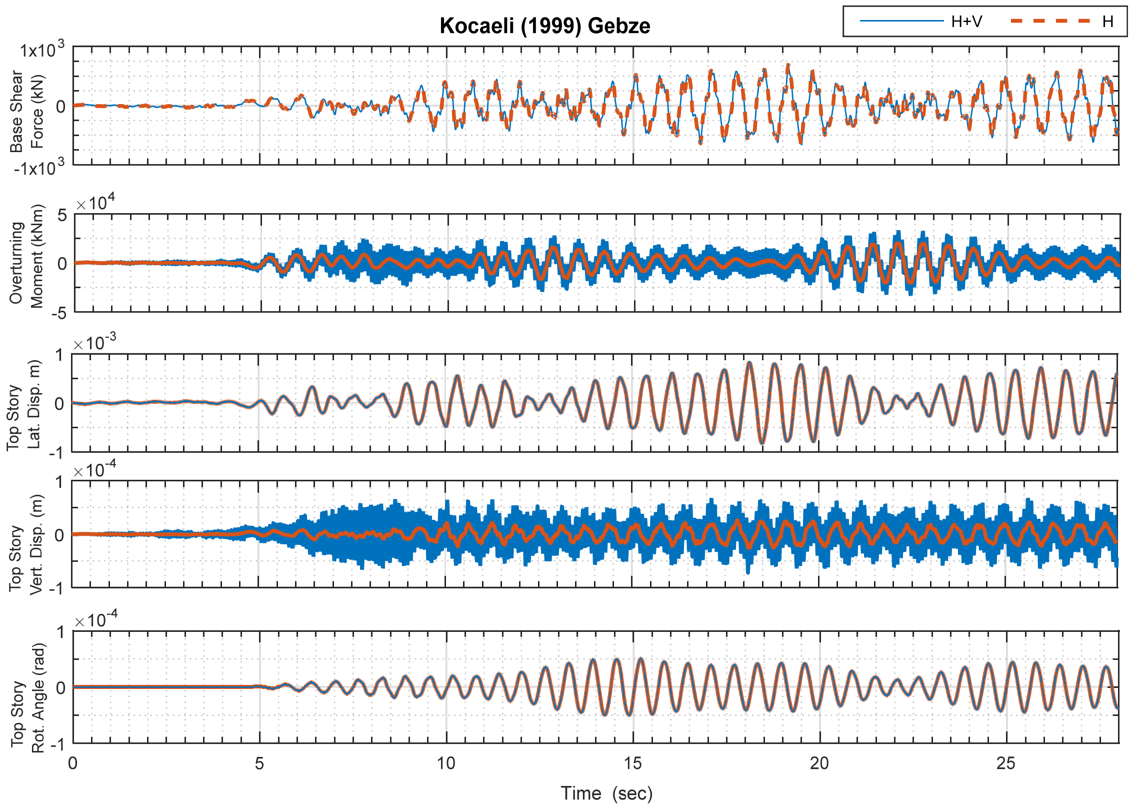


Fig. 8 Analysis results from Kocaeli (1999)

Table 5 The results from Kocaeli (1999)

Kocaeli (1999) Gebze					
Structural Parameter		Horizontal (H)	Horizontal + Vertical (H+V)	Difference (H+V)-(H)	Variation (%)
Base Shear Force (kN)	Max.	6.98×10^2	6.93×10^2	-4.22	-0.60
	Min.	-6.54×10^2	-6.63×10^2	-8.61	1.32
Overturning Moment (kNm)	Max.	20.185×10^3	33.122×10^3	12.937×10^3	64.09
	Min.	-20.150×10^3	-33.150×10^3	-13.0×10^3	64.52
Top Story Vertical Displacement (m)	Max.	2.7×10^{-5}	6.7×10^{-5}	4.0×10^{-5}	154.34
	Min.	-2.6×10^{-5}	-7.3×10^{-5}	-5.0×10^{-5}	183.33

parameters is almost similar in Imperial Valley (1979). All results of interest are presented in Table 4-5 for two earthquake, respectively. From the results, the variation of the base shear force, the overturning moment and the top-story vertical displacement is seen to decrease from Kobe (1995) to Kocaeli (1999). This outcome can be explained with the variation in the V/H ratio. Since Imperial Valley (1979) had the highest V/H ratio in the considered earthquakes, the effects of this earthquake on the structure were larger. Similarly, the effects of Kobe (1995) earthquake, whose

V/H ratio is higher than that of Kocaeli (1999) earthquake, were found to exceed the effects of the Kocaeli (1999) earthquake on the structure. As stated in the previous section, the dominant frequency of the earthquake is also a substantial parameter for these results. For example, the highest amplification in the structural parameters were obtained from Imperial Valley (1979) earthquake since the dominant frequency of the vertical component of this earthquake is very close to that of the structure. Therefore, the frequency content of earthquakes should be considered as an important parameter, and it should be examined accurately before the earthquake analysis.

In Tables 4-5, the base shear force can be observed to decrease in the presence of the vertical earthquake excitation. Such results were related to the reducing effect of the vertical earthquake motion, which means that the horizontal earthquake motion excited the structure in positive direction while the vertical earthquake motion induced in negative direction. Based on the results from these analyses, the overturning moment exhibited the greatest increase among the considered structural parameters in the presence of vertical motion. Since this parameter directly affects sectional capacities of the structural elements (column, beam, shear wall etc.), a structure can remain below the targeted structural performance if exposed to vertical motion as well as the horizontal one.

As shown in Fig. 9, the variation of the base axial force of the R/C structure was also investigated and the results are given in Table 6. The significant increase in the base axial force, ranging between 3000-5600 %, indicated that the seismic performance of the structure completely changed in the presence of the vertical earthquake motion. The vertical motion caused the structure to have a more brittle behavior and to fail to exhibit the desired performance levels during an earthquake. The gradual decrease in the base axial force from Imperial Valley (1979) to Kocaeli (1999) earthquakes showed that the ratio of V/H was a key parameter for the increase in the base axial force.

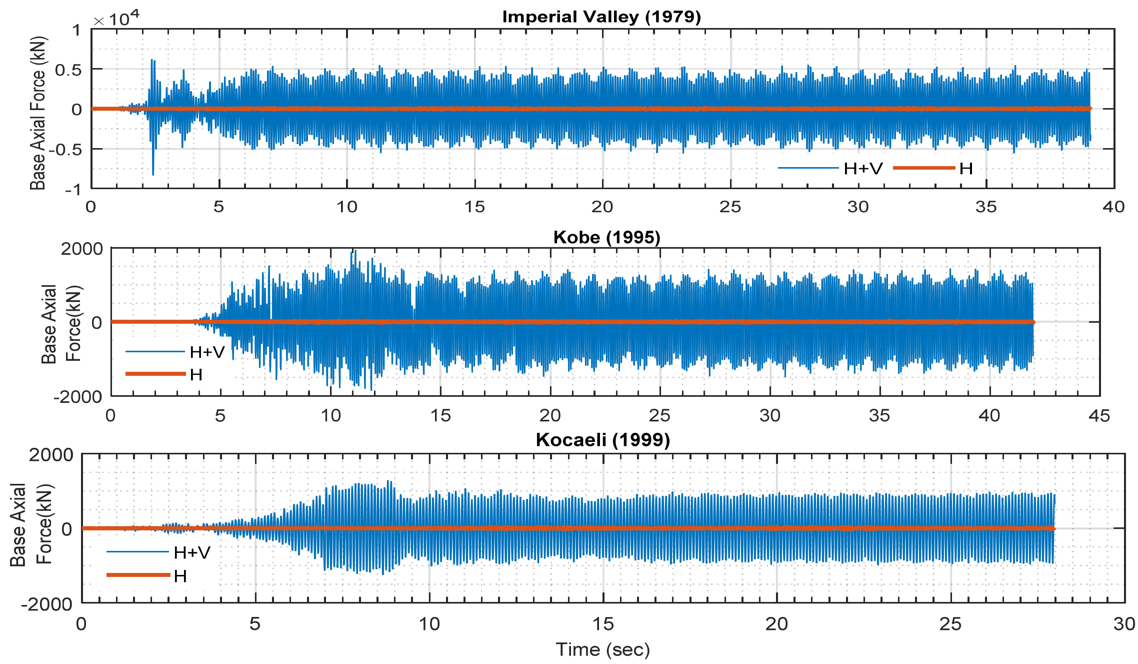


Fig. 9 Base axial force results

Table 6 The results of the Base Axial Force

Base Axial Force (kN)					
Earthquakes		Horizontal (H)	Horizontal + Vertical (H+V)	Difference (H+V)-(H)	Variation (%)
Imperial Valley (1979)	Max.	1.61×10^2	62.09×10^2	60.48×10^2	3759
	Min.	-1.44×10^2	-83.39×10^2	-81.95×10^2	5681
Kobe (1995)	Max.	0.35×10^2	19.32×10^2	18.97×10^2	5396
	Min.	-0.41×10^2	-18.48×10^2	-18.08×10^2	4456
Kocaeli (1999)	Max.	0.37×10^2	12.83×10^2	12.47×10^2	3419
	Min.	-0.39×10^2	-12.52×10^2	-12.13×10^2	3122

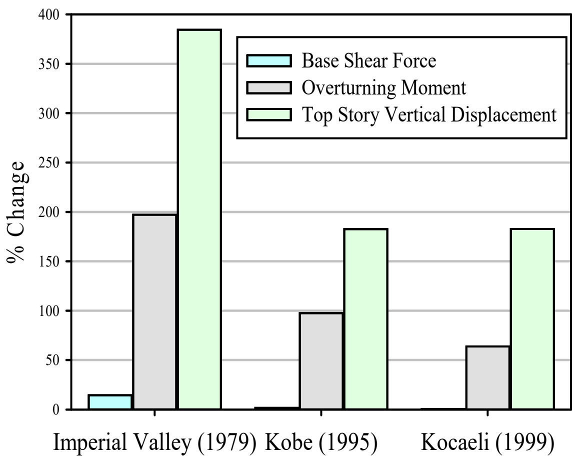


Fig. 10 Change of the parameters

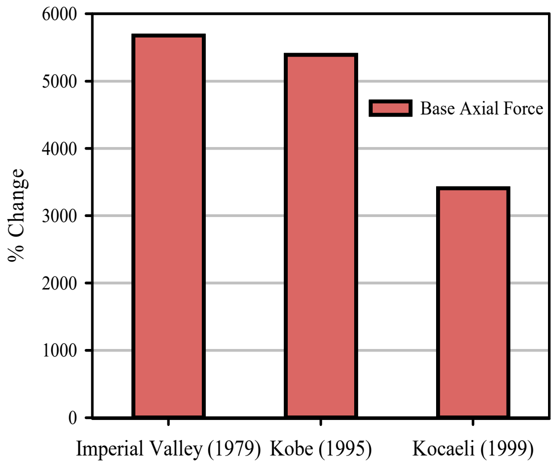


Fig. 11 Change of Base Axial Force

The change of the parameters was summarized for three earthquakes in Fig. 10. The maximum values of the overturning moment and the top-story vertical displacement under Imperial Valley (1979) excitation are almost twice as high as the respective values under the other earthquake excitations. The base shear increases excessively as the V/H ratio increases from Kocaeli (1999) to Imperial Valley (1979) earthquake. Similar change was also obtained for the base axial force as shown in Fig. 11. However, the percent increase in the base axial force can be observed to be relatively higher than the increase caused by the variation of the other parameters. These results indicated that the ratio of vertical to horizontal component (V/H) was determinant parameter to estimate the effect of the vertical earthquake motion on the structure. Besides, this result can be also estimated by conducting a comparative study on frequency content of the vertical earthquake component and dynamic characteristics of structure.

5. Modal damping estimation

Response of structures to the time-history loadings (H and H+V) provides opportunity to compare modal frequency and to obtain the variation of modal damping ratio. With the help of the dynamic analysis of numerical model of the structure, modal frequency of each mode can be predicted using response acceleration records under the earthquakes. Although the response acceleration data obtained from the analysis cannot feature the data from experimentally monitoring, the response data provide the essential information to determine the effect of the vertical earthquake motion on modal damping estimation of the structure. Besides, collecting data from instruments under earthquake motions may not always be possible due to its difficulty and higher costs. For this aim, two response acceleration records obtained from the top-story lateral displacement and the top-story vertical displacement were utilized to determine dominant frequency of the lateral and the vertical modes separately for H and H+V loadings. In order to obtain these dominant frequencies, the frequency-domain analysis of the acceleration records was carried out using powerful tools of Fast Fourier Transformation (FFT).

$$\zeta_n = \frac{f_b - f_a}{2 f_n} = \frac{1}{2} \frac{\Delta f}{f_n} \tag{1}$$

$\zeta_n = n_{th}$ modal damping ratio

$f_n = n_{th}$ modal natural frequency

Δf = the band width in frequency domain corresponding $A_{max}/\sqrt{2}$

A_{max} = the amplitude of n_{th} modal frequency (f_n)

f_b, f_a = corresponding ends of bandwidth (Δf)

Using these FFT spectrums, the variation of lateral and vertical modal damping ratio of the structure was estimated. For this aim, commonly well-known approach of half power bandwidth method was considered. The method is very practical for preliminary estimation of damping ratio. In this method, the basic formulation of Eq. (1) was used. Besides, general steps of the approach are summarized in Fig. 12.

Based on the frequency-domain analysis of the response acceleration records, the lateral dominant frequency values were obtained to be 1.41 s^{-1} corresponding period of 0.709 sec for both H and H+V loading conditions. The frequency-domain analysis of the records for all earthquakes is given in Fig. 13(a) for H loading and Fig. 13(b) for H+V loading. When it comes to comparing the results obtained from the dynamic analysis with those obtained from FFT analysis of response acceleration records, almost identical frequency/period values were reached. This outcome showed

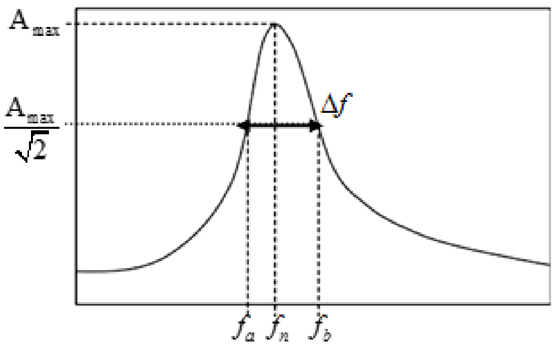
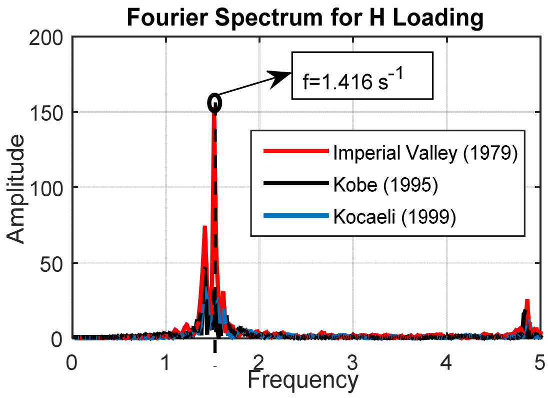
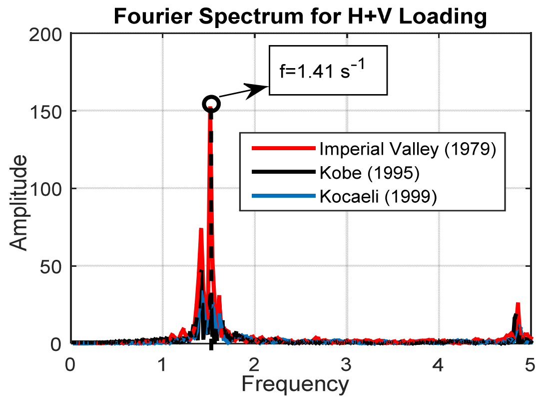


Fig. 12 Half power bandwidth approach

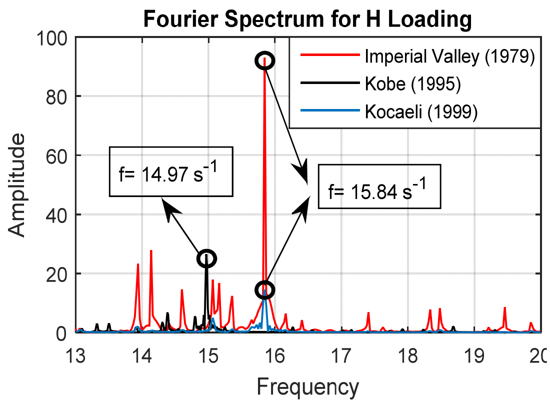


(a) H loading

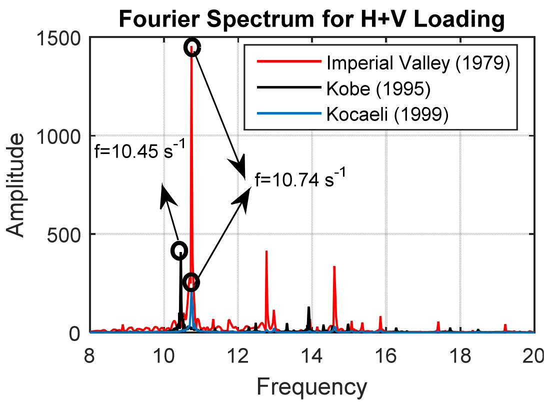


(b)) H+V loading

Fig. 13 FFT of lateral response acceleration data



(a) H loading



(b) H+V loading

Fig. 14 FFT of vertical response acceleration data

a good agreement between two analyses. In addition, the vertical earthquake excitation cannot increase the amplitude in lateral direction by assuming that the top-story lateral displacement remains constant under the vertical earthquake motion. Thus, the vertical earthquake motion has no considerable effect on lateral response of the structure, no matter what its peak acceleration value is. In other words, the vertical earthquake motion can be ignored when estimating the lateral response of the structure. Based on the number of earthquakes, these conclusions can change. Therefore, the results obtained from this study should be considered to make estimations of the response of the structure under the vertical earthquake motion.

Similar analysis were conducted for vertical response of the structure. In contrast to lateral response, the vertical earthquake action relatively affected the frequency-domain behavior of the structure. As shown in Fig. 14(a) and Fig. 14(b), the vertical dominant periods were obtained for all earthquakes under H and H+V loading conditions. The effect of the vertical earthquake motion was determined through comparing the results from H loading to those from H+V loading. FFT results obtained under H+V loading were compatible with the dynamic analysis results. However, the results from the H loading remained on the conservative side. In addition, amplitude in vertical

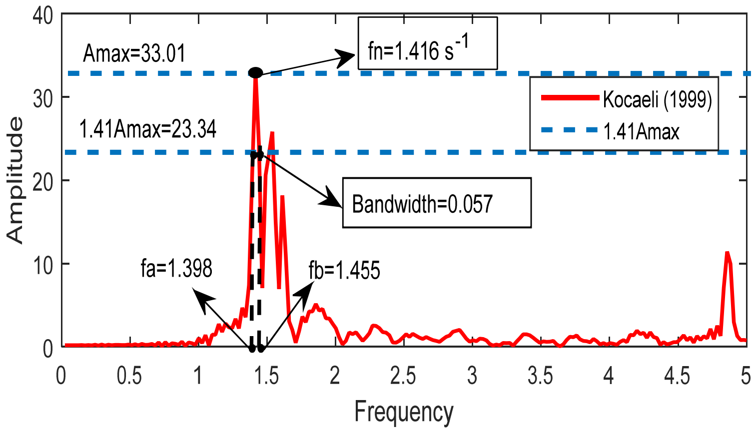


Fig. 15 Lateral damping estimation using Kocaeli (1999)

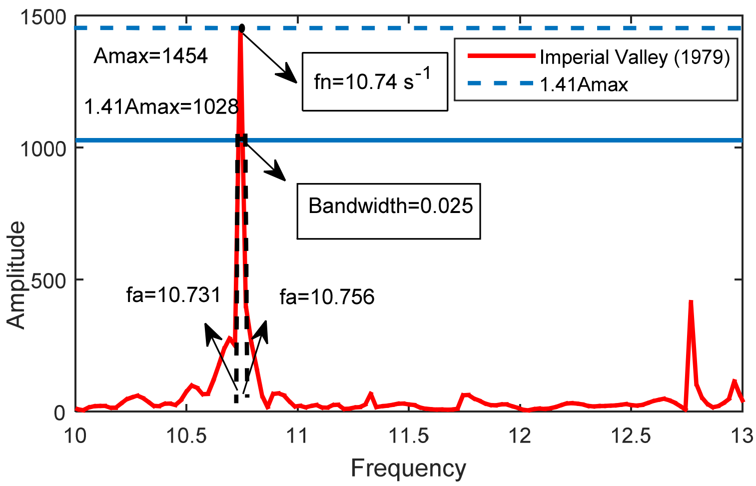


Fig. 16 Vertical damping estimation using Imperial Valley (1979)

direction significantly increased in the presence of the vertical earthquake motion. Although the same frequency value of 1.41 s^{-1} in lateral direction was obtained for all earthquakes under both loading conditions, Kobe (1995) earthquake had a different frequency value from the others in vertical direction. All results were close and they noticeably showed good agreement with the dynamic analysis results. Modal damping ratio of the structure under the earthquake loads and its variation were also investigated using the fundamental method of half power bandwidth. The results obtained under earthquake loading without the vertical earthquake motion were taken into account as reference values to indicate the effect of the vertical earthquake motion on modal damping of the structure. This investigation was conducted for each earthquake utilizing the response accelerations in horizontal and vertical directions.

Considering the parameters given in Fig. 15, the horizontal damping ratio was calculated to be 2.5% for each earthquake under both loading conditions. Although 5% damping ratio was expected form the analyses of the R/C structure, the half of this damping value of 2.5% was obtained. This consequence was based on the assumptions in the model. To illustrate, cover concrete and confined concrete models and their properties, and the contribution of stirrup to ductility of the system were not defined due to the linear time-history analysis. Therefore, the calculated damping ratio of 2.5% was decided to be used for comparative study. Since identical results were obtained for different earthquakes and for both loading conditions, only the results of Kocaeli (1999) earthquake with the vertical earthquake motion were presented. Based on these results, the vertical earthquake motion has no effect on horizontal modal damping of the structure.

The parameters of the vertical earthquake motion of Imperial Valley (1979) are shown in Fig. 16. Imperial Valley (1979) earthquake was considered in this analysis owing to its high vertical peak acceleration value. Under H loading, vertical modal damping ratio was calculated as approximately 0.05%. Under H+V loading, this value was obtained to be 0.1%, implying an increase of 100% in the value of the damping ratio in the presence of the vertical earthquake motion. From the analysis of each earthquake, it was obtained that the damping ratio was reversely proportional with the V/H ratio. The variation of vertical modal damping ratio in the other earthquakes, Kobe (1979), Kocaeli (1979), was determined 3.0% and 2.0%, respectively.

6. Conclusions

The current study is aimed at identifying the effect of the vertical earthquake component on the behavior of a high-rise R/C structure. For this purpose, first of all, the seismic behavior of an example R/C structure was evaluated for three different earthquake records with varying the vertical-to-horizontal peak acceleration ratio. The values of the base shear force, the overturning moment, the top-story lateral displacement, the top-story vertical displacement and the top-story rotation angle of this structure were determined in time domain in the absence and presence of the vertical earthquake motion. Secondly, using the response acceleration data obtained from earthquake analyses, damping ratio of the structure in horizontal and vertical directions was estimated through the frequency-domain analysis. In addition, the effect of the vertical earthquake motion on damping ratios of the structure was investigated. Making a comparative study on the structural parameters stated above and modal damping estimation of the structure, the following outcomes were obtained:

- The overturning moment and the top-story vertical displacement significantly increase under an earthquake with vertical component. Although the vertical earthquake motion was expected to influence the base shear force, such a variation was not observed in the analyses. The top-story lateral displacement and the top-story rotation angle were also observed to exhibit little or no change in the absence or presence of the vertical earthquake motion in addition to the lateral one.
- The base axial force variation results denoted that the tensile/compressive forces in the columns and piers increased considerably under the coupled earthquake motion and this increase caused the structure to exhibit a more brittle behavior. Hence, additional requirements should be recommended to increase the ductility and energy absorption capacities of these structural members, including but not limited to improved lateral confining reinforcement arrangements.
- Based on the results from the analyses, the vertical to horizontal peak acceleration (V/H) ratio is a significant parameter for identifying the effect of the vertical earthquake motion on the structural behavior.
- In addition to V/H ratio, the dominant frequency of the vertical earthquake motion is also

effective in increasing the displacements and internal forces of a structure. This effect increases considerably if the dominant frequency of the vertical earthquake motion is close to that of the structure. Similar results were obtained from the earthquake intensity analyses. High frequency content gives rise to an increase in the effective earthquake duration, and thus an increase in the values of the structural parameters.

• Response acceleration records obtained from the analyses can be used for modifying the dynamic characteristics of a structure. For this objective, the frequency-domain analyses of the response accelerations need to be conducted using FFT. The analyses conducted within the scope of the present study indicated that the frequency-domain analysis and the dynamic analysis of a structure were generally in good agreement.

• Modal damping ratios of a structure can also be estimated using the frequency-domain spectrums. For this aim, the half power bandwidth method was utilized in the present study. The example R/C structure was found to have identical horizontal modal damping ratio (2.5%) for all earthquakes scenarios used in the analyses. Accordingly, the horizontal modal damping is not influenced by the presence and magnitude of the vertical earthquake motion. The vertical modal damping of a structure, on the other hand, increases with the V/H ratio of the earthquake.

Based on the results obtained from the analyses, the following recommendations below are given in the study.

• The vertical earthquake motion may lead to the change in earthquake performance of a structural element and the entire structure due to the significant increase in the overturning moment.

• Some idealizations considered in design/analysis stage may not be accepted. For example, the rigid diaphragm assumption for the slab may not be valid in the presence of the vertical earthquake motion due to the high vertical displacements leading to out of plane behavior.

• Near-field earthquake ground motion with high V/H ratio should be used for the time-history analysis.

• The frequency content of earthquakes to be considered should be analyzed to present valuable information for the effect of the vertical earthquake motion.

• Vertical modal damping of structures should be estimated by taking the vertical earthquake motion into consideration.

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