VERTICAL GROUND MOTION EFFECTS ON THE INTERNAL FORCES IN REINFORCED CONCRETE STRUCTURES

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Abstract

This article investigates the effects of vertical ground motion on the seismic responses of reinforced concrete (RC) structures. Conventional seismic design primarily focuses on horizontal ground motions, often neglecting the significant impacts of vertical accelerations. This study begins with a comprehensive analysis of the characteristics of vertical ground motion, thereby enhancing the understanding of these loads. A numerical analysis is performed on a typical multistorey RC building model to evaluate the impact of vertical ground motion on internal forces, specifically axial forces in column elements and bending moments in beam elements. The findings show that vertical ground motion can result in substantial increases in internal forces, which may necessitate revisions to current design practices. This study emphasizes the importance of considering vertical ground motion in the seismic-resistant design of RC structures to ensure safety and structural integrity.

Keywords: *Seismic analysis; elastic response spectrum; vertical ground motion; reinforced concrete building.*

1. Introduction

An earthquake is the shaking of the Earth's surface caused by an unexpected release of energy within the lithosphere, which generates seismic waves. There are three main ways that these seismic waves travel, and each has a particular effect on structures such as [1]:

- P-waves (Primary waves): These are compressional waves that move through the Earth in a push-pull motion, expanding and compressing the material in their passageways.

- S-waves (Secondary waves): These shear waves cause particles to move perpendicular to the direction of motion, generating shaking that is either up and down or side to side.

- Surface waves: These waves travel along the Earth's surface and typically cause the most damage during an earthquake. They include Love waves (the waves move horizontally in a side-to-side motion, creating a rolling effect) and Rayleigh waves (the waves produce an elliptical rolling motion similar to ocean waves, causing both vertical and horizontal ground movements).

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Different wave types interact with structures in different ways, producing diverse impacts based on the structure of the building and the type of seismic activity [2, 3].

At earthquake monitoring stations, seismometers record three (orthogonal) components of motion (i.e., seismograms) in three directions: up-down, north-south, and east-west, which correspond to three spatial axes. Observations from earthquake records at seismic stations reveal that P-waves are more prominently detected in the vertical component, while S-wave amplitudes are generally larger in the horizontal components. Vertical ground motions caused by P-waves exhibit different characteristics compared to horizontal motions [4-7]. In addition, compared with S-waves, P-waves, which are responsible for horizontal ground motions, travel faster with a higher frequency.

In earthquake engineering, horizontal ground motions are typically the primary focus in seismic design, since it is retained that most of the damage is due to the horizontal component, particularly to RC structures, while the vertical ground motion component is not frequently considered. However, observations from recent earthquakes are leading to a significant shift in current research and design trends, altering the traditional understanding of these concepts.

Currently, the significance of the vertical seismic component in seismic-resistant design is open to discussion. However, vertical seismic impacts can be critical for certain types of structures or structural elements, such as cantilever beams. Specifically, according to many research results, vertical motions may also have significant impacts on buildings, especially for tall or long, slender structures.

Many earthquake design standards do not include the vertical elastic response spectrum. When it is referenced, it is typically represented as the horizontal spectrum multiplied by a reduction factor (typically 1/3) [8-10]. Observations from seismic accelerations near fields have demonstrated that, in the short term, the vertical seismic component can exceed the horizontal one. Additionally, the frequency content of the vertical response spectrum generally differs from that of the horizontal spectrum. This discrepancy significantly alters seismic calculations when considering the impact of vertical ground motion compared to those that consider only the horizontal component.

Current seismic codes recommend a vertical spectrum with values ranging from 1/2 to 2/3 of the horizontal component. However, this approach appears to be unconservative and directly contradicts based on recent measurements. In recent earthquakes, the vertical component of ground motion has been observed to reach values even exceed the horizontal component. Following many destructive earthquakes, engineers have noted structural damage such as buckling of large columns and fractures in large-diameter reinforced concrete columns supporting buildings and freeway structures that is attributed to strong vertical ground motion. Consequently, neglecting the vertical ground motion component in seismic design could result in significant, unquantifiable risks of collapse, especially for structures located in the near field [4, 5, 7].

The effect of vertical ground motion on building structures can be substantial, although it is often less emphasized compared to horizontal components. Some notable impacts of vertical ground motion on building structures include:

- Increased vertical loads: It can lead to increased dynamic loads on a structure. Buildings not designed to handle these additional loads may suffer from overstressed structural components.
- Load redistribution: It can alter the distribution of loads within the building, potentially leading to uneven stress and strain in various parts of the structure.
- Overturning moments: For tall or slender buildings, vertical ground motion can increase the overturning moments, affecting the stability, particularly in structures with high aspect ratios or those that are top-heavy.
- P-Δ effects: Vertical accelerations can exacerbate P-Δ effects (additional moments due to lateral displacements), impacting overall stability and increasing the risk of structural failure.
- For the dynamic response of structure, vertical ground motion can influence the natural frequency of a building, leading to the change of the structural vibrational characteristics, potentially interacting with its horizontal response.
- Significant amplitude or frequency of vertical ground motion may induce resonance effects in structures with vertical irregularities or long-span elements.
- Vertical ground motion can influence the performance of foundations, affecting soil-structure interaction and potentially leading to differential settlements or increased bearing pressures.
- Vertical accelerations can impact non-structural components such as ceilings, partitions, and equipment, which might experience additional forces and displacements, leading to potential damage or failure.

Above discussions indicate that vertical ground motions can affect reinforced concrete buildings by increasing vertical loads, altering stability, impacting dynamic response, influencing structural and non-structural elements, and increasing the risk of structural failure. Incorporating considerations for vertical ground motion in seismic design is crucial to ensure the structural integrity and safety of buildings, especially in areas prone to significant seismic activity.

2. Objective and methodology

The primary objective of this study is to investigate the effect of vertical ground motion on the responses of multistorey RC buildings.

To achieve this goal, the following methodologies have been identified:

- A comprehensive study of the key characteristics of vertical ground motion to enhance understanding of this type of load and the mechanism of its impact on the structure.

- The definition of the horizontal elastic response spectrum according to the Vietnam Standard (TCVN 9386:2012 [11]) along with the specified conditions for calculation.

- Numerical analysis on a typical RC building model to investigate the effect of vertical ground motion on internal forces, including axial force and bending moment within the structure.

3. Vertical component of ground motion

3.1. Characteristic of vertical ground motion

The vertical component of an earthquake refers to the up-and-down movement of the ground. Unlike horizontal motion, which is more directly responsible for building swaying and damage, vertical motion involves the ground moving perpendicular to the Earth's surface. Therefore, vertical acceleration has several distinctive properties that distinguish it from the horizontal component, namely:

- The amplitude of vertical motion is generally smaller compared to horizontal motion. This is because most seismic energy is released in the horizontal directions.

- The vertical ground motion is associated with the arrival of vertically propagating P-waves, while the horizontal component is more of a manifestation of S-waves. The wavelength of P-waves is shorter than that of S-waves, which means that the vertical ground motion has much higher frequency content than the horizontal component.

- The significance of the vertical ground motion is often characterized by the vertical-horizontal peak ground acceleration (V/H) ratio. Many codes suggest scaling of a single spectral shape, originally derived for the horizontal component using an average V/H ratio of 2/3. This procedure was originally proposed by Newmark *et al.* [12]. As a result, all components of motion have the same frequency content in almost design codes. The frequency content, however, is demonstrably different, as discussed above. Also, the ratio of 2/3 for V/H is unconservative in the near-field and overconservative at large epicentral distances.

Turkey-Syria earthquake 2023 is taken as a specific earthquake for demonstrate the above discussion. Fig. 1(a) presents the time-history accelerations of the earthquake. As shown in Fig. 1 and Table 1, the vertical component has a much higher peak ground acceleration than the two-horizontal component. The ratio of V/H for a such earthquake is 1.722 (for the minor horizontal component) and 1.433 (for the major horizontal component).

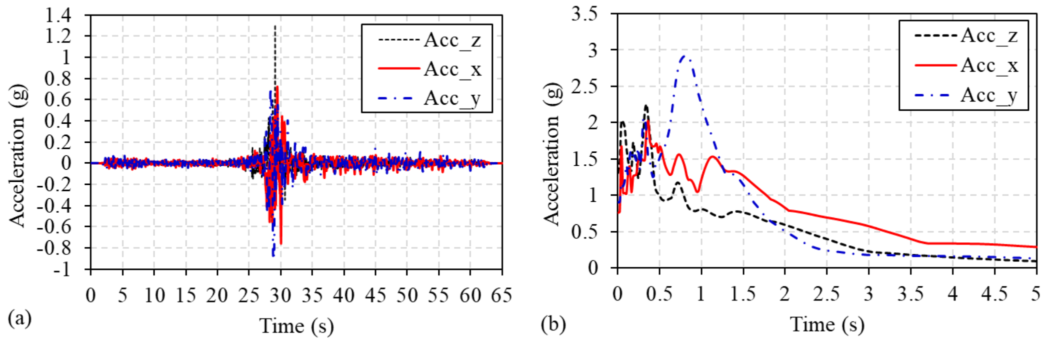


Fig. 1. Turkey-Syria earthquake 2023 (Int-20230206_0000008, Hassa-Hatay, 3138, TNSMN, Turkey): (a) Time history acceleration, (b) Response spectra.

Table 1. PGA of Turkey-Syria earthquake

	Acc_x	Acc_y	Acc_z	Acc_z / Acc_x	Acc_z / Acc_y
PGA	0.760	0.907	1.308	1.722	1.433

Figure 1(b) shows the elastic response spectra of three components. Accordingly, the energy content of vertical wave component is concentrated mainly on short periods (i.e., high frequency).

3.2. Vertical elastic response spectrum

- Calculate vertical elastic response spectrum according to TCVN 9386:2012.

TCVN 9386:2012 has the advantage of defining the vertical response spectrum independently, rather than relying on the horizontal spectrum. Accordingly, the vertical elastic response spectrum is defined by the following expressions:

$$0 \le T \le T_B:\ S_{ve}(T) = a_{vg}\left[1 + \frac{T}{T_B}(3.0\eta - 1)\right]$$

$$T_B \le T \le T_C : S_{ve}(T) = 3.0 a_{vg}\eta$$

$$T_C \le T \le T_D : S_{ve}(T) = 3.0 a_{vg}\eta \frac{T_C}{T}$$

$$T_D \le T \le 4s : S_{ve}(T) = 3.0 a_{vg}\eta \frac{T_C T_D}{T^2}$$

where $S_{ve}(T)$ is the vertical elastic response spectrum, T is the vibration period; T_B, T_C, T_D are the parameters of spectral acceleration branch, a_{vg} is the design ground motion that is determined based on the value of a_g (a_g is the design ground acceleration on type A ground), η is the damping factor, determined by the viscous damping ratio of structure ξ (%).

The recommend values of the parameters describing the vertical elastic response spectra are expressed as follows:

Table 2. Parameters describing the vertical elastic respons spectra

a_{vg}/a_g	T_B (s)	T_C (s)	T_D (s)
0.90	0.05	0.15	1.0

Compared with the horizontal response spectrum, we can see that in addition to the calculated a_{vg} value of $0.9a_g$, the vertical acceleration component does not include the soil factor (i.e., factor S). Further, the oscillation period bands in the acceleration response spectrum diagram are also significantly smaller. The comparison details are shown in Fig. 2.

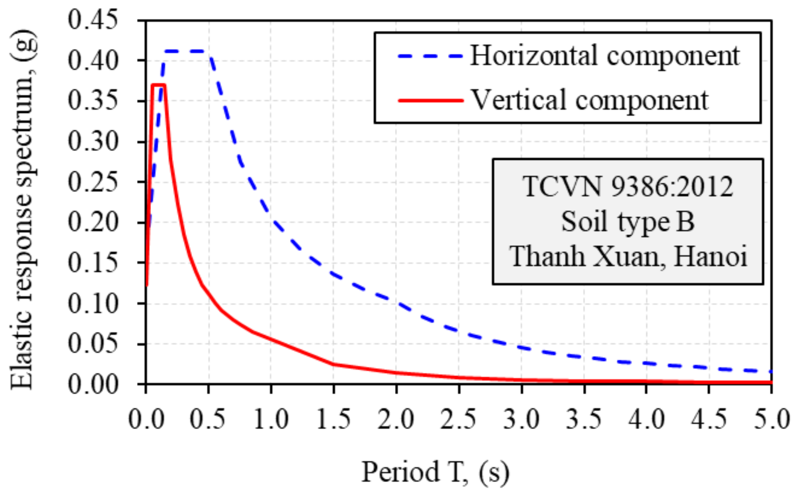


Fig. 2. Elastic response spectrum for Thanh Xuan, Hanoi.

- Regulations for considering the vertical component of earthquakes

According to TCVN 9386:2012, the vertical component of the seismic action is considered only when the peak ground acceleration (PGA) of the ground motion is greater than 0.25 g and in the following cases: For horizontal or nearly horizontal structural members spanning 20 m or more, for horizontal or nearly horizontal cantilever components longer than 5 m, for horizontal or nearly horizontal pre-stressed components, for beams supporting columns, and in base-isolated structures.

4. Numerical study

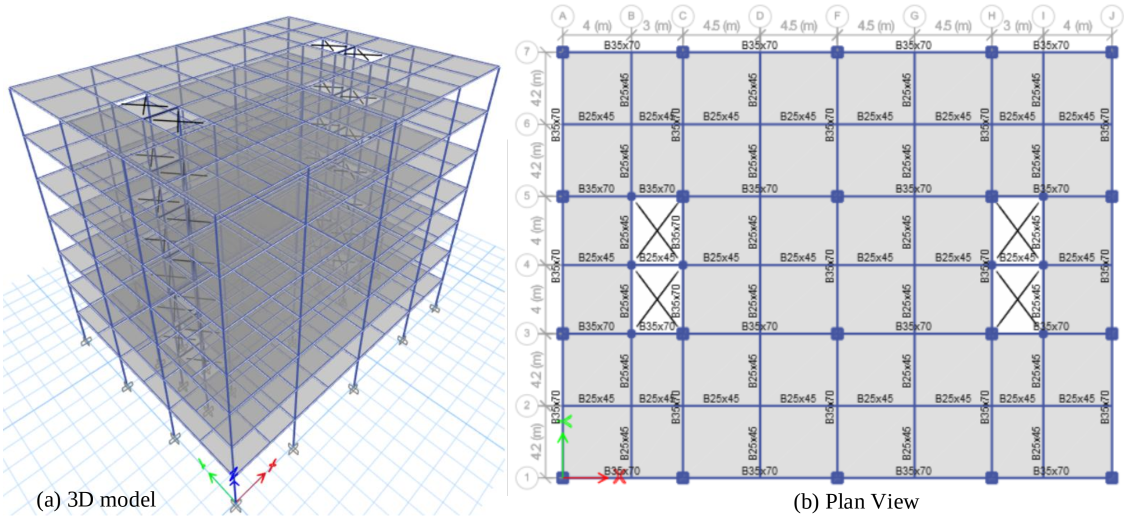
4.1. Analysis model

This study performs a typical multistory reinforced concrete building model located in Thanh Xuan, Hanoi. The numerical model of the building structure was established using Etabs V.19 software, as illustrated in Fig. 3. Accordingly, the building features plan dimensions of 32.0 m × 24.8 m, with a story height of 3.9 m for the first floor and 4.1 m for the upper floors. The concrete grade used is B25, while the reinforcement grade is CB400-V.

Columns from the first to fourth stories have cross-sectional dimensions of 60 cm × 60 cm. In the fifth to seventh stories, the column dimensions are reduced to 50 cm × 50 cm.

The main beams have cross-sectional dimensions of 35 cm × 70 cm, while the sub-beams measure 25 cm × 45 cm.

The thickness of the concrete floors is 15 cm.



(a) 3D model (b) Plan View

Fig. 3. Numerical model of a typical RC building for analysis.

The considered loading includes: dead load (DL) 1.15 kN/m^2, live load (LL) 2.0 kN/m^2 on the floor and 0.9 kN/m^2 on the roof. The mass source for seismic analysis includes DL + 0.24LL; the building is supported on soil type B, with 5% damping. Assume that the connection between the bottom of column and the foundation is rigid.

In the framework of this article, the analyses were performed only with accelerograms that are automatically calibrated by Etabs software in frequency domain to match the elastic response spectrum defined in TCVN 9386:2012. The elastic response spectra of horizontal and vertical ground motions are presented in Fig. 2.

For this study, the authors perform only one horizontal earthquake load component (the major component) acting independently in Ox-direction of the building. Consequently, the load combination is determined COM1 (DL + LL + EQx + 0.3EQv).

- Parametric study

To achieve the research objectives, the results from the parametric study include: The seismic responses, specifically axial force and bending moment, of the building structure subjected to vertical ground motion. A comparison of the axial force and bending moment in the structure due to vertical ground motion against other loads (i.e., dead load, live load, and horizontal ground motion); and an evaluation of the impact of the vertical earthquake component in the load combination on structural responses.

4.2. Results and discussion

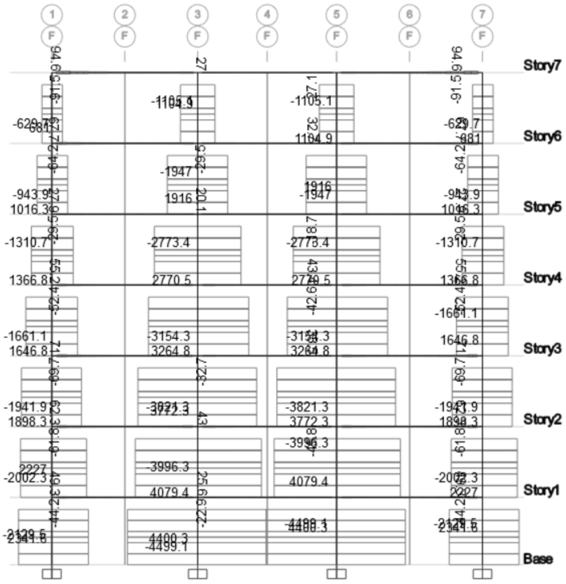
The peak response of axial load and bending moment of the building subjected to vertical ground motion are presented in Fig. 4(a) and 4(b), respectively.

As shown in the figures, the axial force in the column is significant, gradually increasing from top to bottom, which aligns with expected behavior. Notably, axial tensile forces present throughout the entire column structure, approximately equal to the compressive force. For instance, at the base of the column at axis F-5, the axial tensile force is 4400.27 kN while the compressive force is 4499.14 kN.

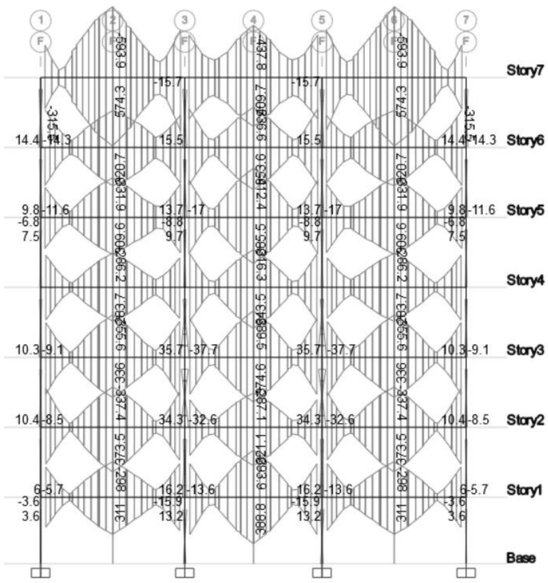
Similarly, Fig. 4(b) illustrates the bending moments in the structures, predominantly occurring in the beam elements, with significant positive and negative values observed. Additionally, the peak bending moment increases with the height of the structure.

The obtained results demonstrate significant impacts of vertical ground motions on the seismic responses of the structure in general and the RC building in particular.

The comparison of axial forces in columns under different types of loads is presented in in Fig. 5. Accordingly, the axial force values induced by dead loads and live loads are consistently compressive. Meanwhile, the horizontal earthquake component generates axial forces with both tensile and compressive phases in the columns; however, these values are negligible compared to the dead and live loads and can be effectively ignored. On the other hand, the axial forces (both compression and tension) resulting from the vertical acceleration impact are even greater than those from traditional load types (i.e., dead load and live load). These differences are detailed in Table 3 and Fig. 6.



(a) Axial force (kN)

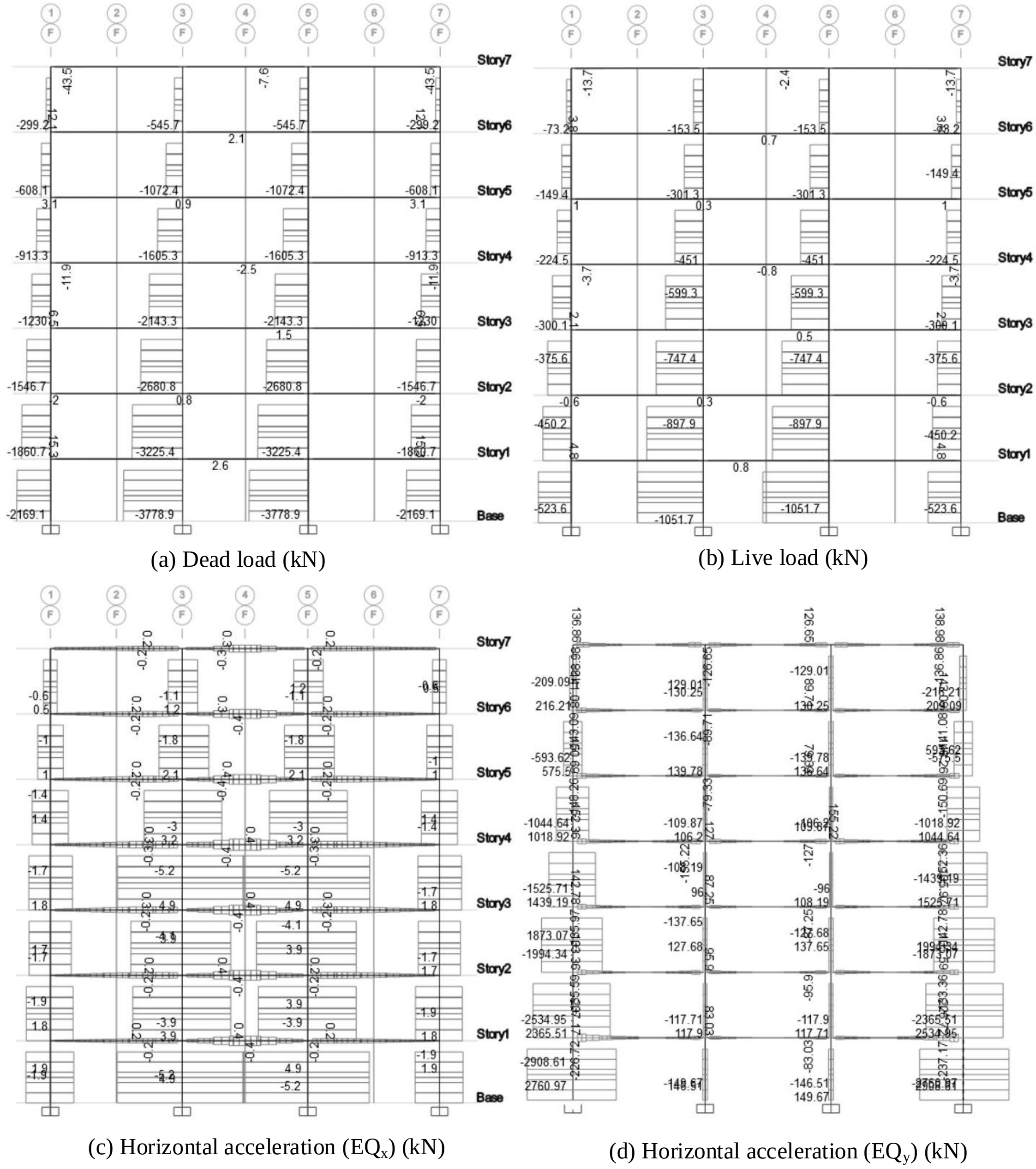


(b) Bending moment (kN/m)

Fig. 4. Axial force and bending moment of building subjected to vertical ground motion (axis F).

Table 3. Comparison of axial force response in columns

Story	DL (kN)	LL (kN)	EQx (kN)	EQy (kN)	EQz (kN)	EQx (kN)	EQy (kN)	EQz (kN)
Axis	F-5					F-1		
7th floor	545.7	153.5	1.1	130.3	1105.1	0.56	216.2	681.0
4th floor	1605.3	451.0	3.2	108.2	2770.5	1.75	1525.7	1661.1
1st floor	3778.9	1051.7	5.2	149.7	4499.3	1.95	2908.6	2341.6



(a) Dead load (kN)

(b) Live load (kN)

(c) Horizontal acceleration (EQ_x) (kN)

(d) Horizontal acceleration (EQ_y) (kN)

Fig. 5. Comparison of the axial force of RC building subjected to different loadings (axis F).

Similarly, Fig. 7 presents the comparison of bending moment (M3) in the structures subjected to different loads. As observed from the figures, dead load and live load cause bending moment in the beam with monotonic form (i.e., the two ends of the beam are negative moment, the middle of the beam is positive moment). The horizontal ground motion mainly causes bending moments (with negative and positive phases) in the columns. On the other hand, the vertical ground motion primarily induces bending moment in beam elements, as the observation presented above. The two distinct behaviors of the structural response to horizontal and vertical seismic component indicate that considering only the horizontal ground motion may overlook important responses of the beam elements to vertical ground motion. This is particularly relevant given the significant bending moment values observed in the beam elements due to vertical ground motions. Details of the comparison results are presented in Table 4.

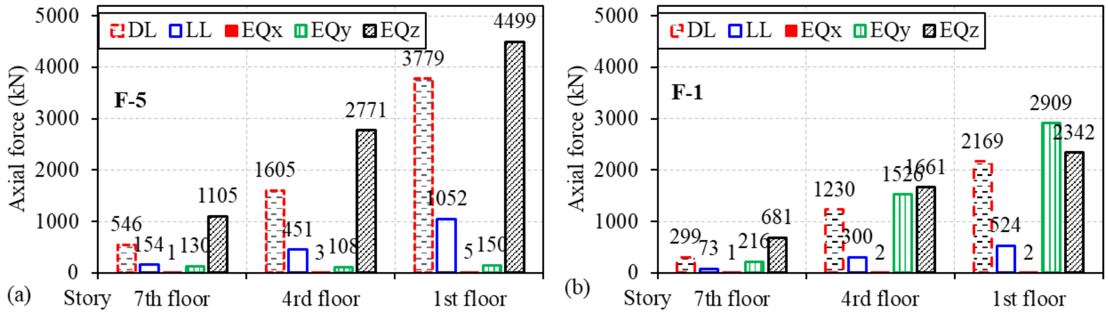


Fig. 6. Comparison of the axial force of RC building subjected to different loadings.

Table 4. Comparison of bending moment response in beam elements (span 3-5, axis F)

Story	DL (kN.m)	LL (kN.m)	EQx (kN.m)		EQz (kN.m)	
			max	min	max	min
7th floor	112.950	34.110	0.520	-0.590	409.720	-437.790
4th floor	119.420	36.090	1.260	-1.310	343.510	-316.330
1st floor	118.530	35.770	1.270	-1.270	388.810	-393.890

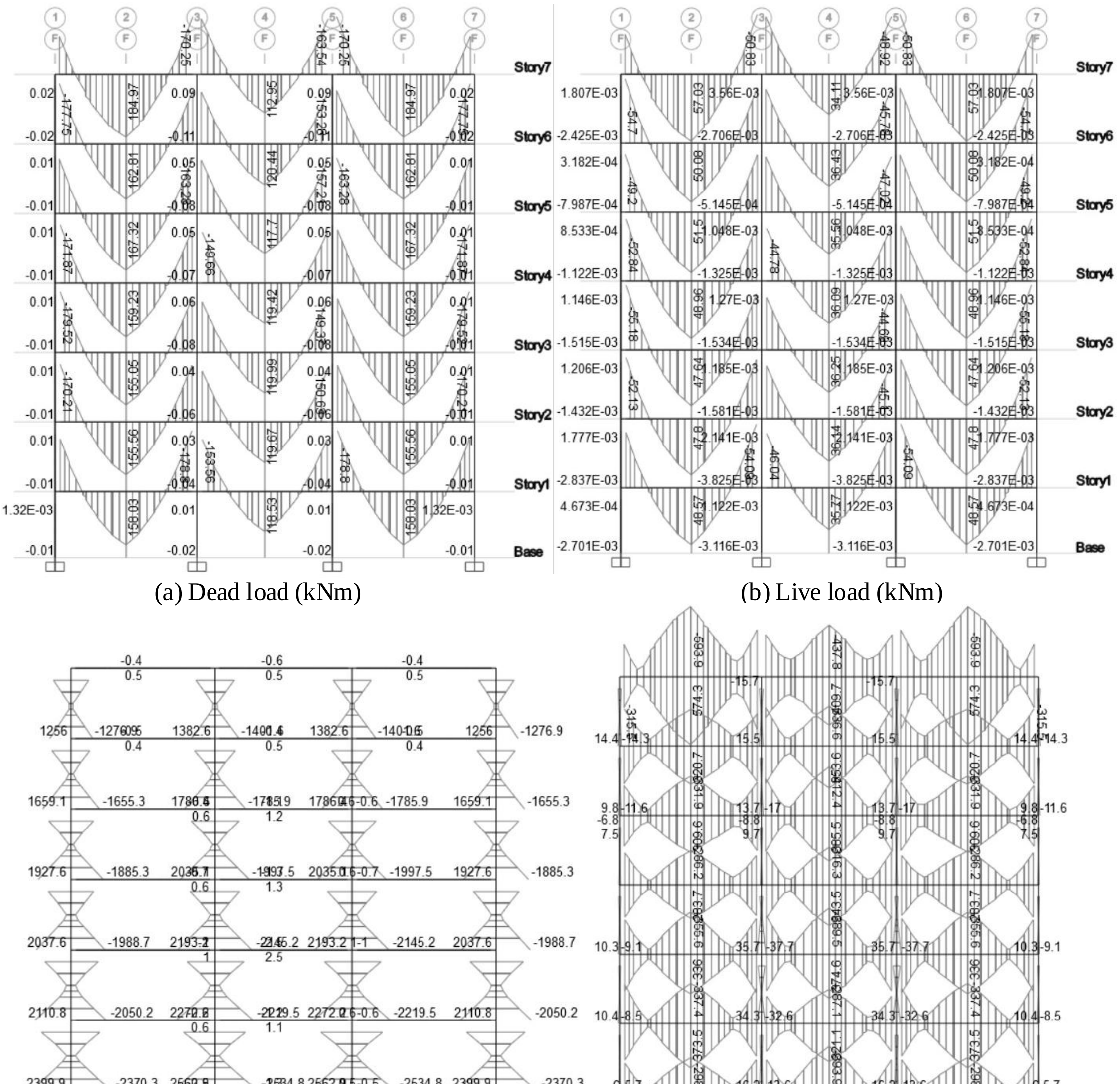
The contribution of vertical ground motion to total axial force is considered through the structural responses of building subjected to load combination. Accordingly, four load combinations are investigated, including:

COMB-1 (1DL + 0.8LL + EQx + 0.3EQy),

COMB-2 (1DL + 0.8LL + EQx + 0.3EQy + 0.3EQz),

COMB-3 (1DL + 0.8LL + 0.3EQx + EQy),

COMB-4 (1DL + 0.8LL + 0.3EQx + EQy + 0.3EQz)

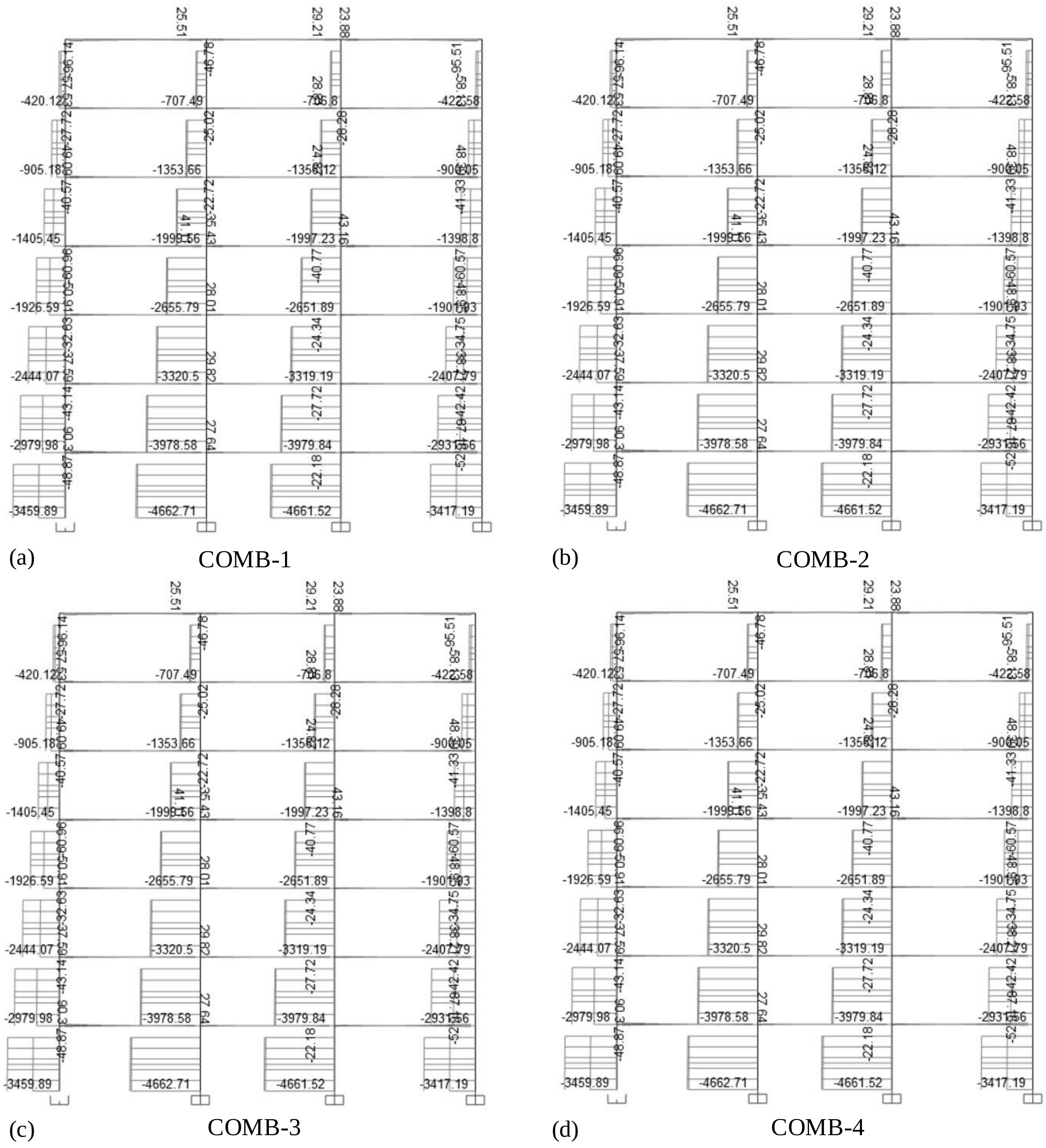


(a) Dead load (kNm) (b) Live load (kNm)

(c) Horizontal acceleration (EQ_x) (kNm) (d) Vertical acceleration (kNm)

Fig. 7. Comparison of the bending moment of RC building subjected to different loadings.

Figure 8 presents the comparison of the axial responses of structures under four load combinations.



(a) COMB-1 (b) COMB-2

(c) COMB-3 (d) COMB-4

Fig. 8. Contribution of vertical ground motion on the axial response of structure subjected to load combinations.

Figure 9 presents the comparison of the bending moment of structures under four load combinations.

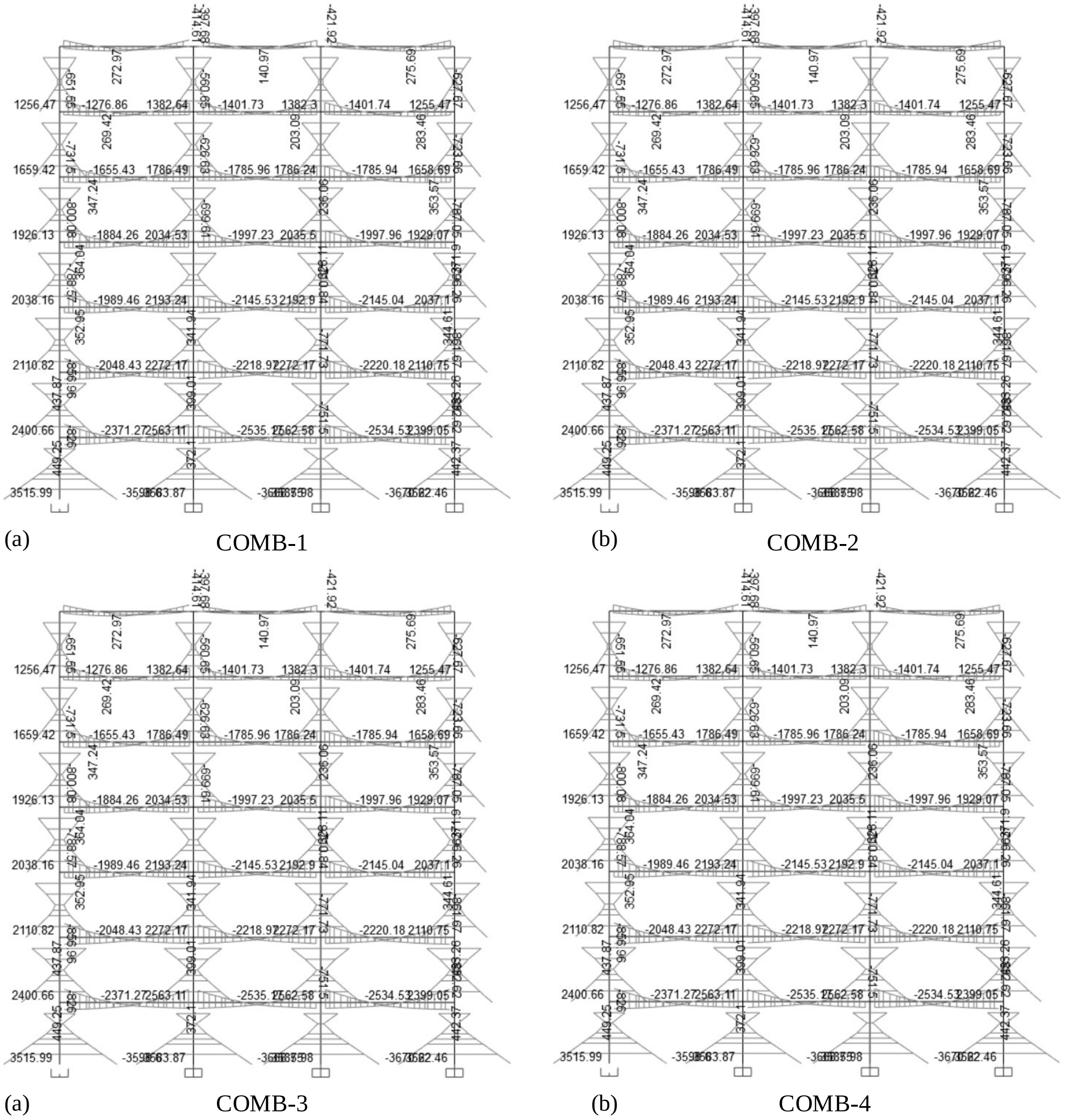


Fig. 9. Contribution of vertical ground motion on the bending of structure subjected to load combinations.

As observed in the figures, the contribution of vertical acceleration to the internal forces of structure, especially the axial force in this case study, is considerable, even though it is calculated using a much smaller factor (30%) compared to the other types of loads. Notably, the axial force in column elements increases by approximately 20% to 30%. In the author's opinion, this increase is substantial and can lead to important changes in the seismic-resistant design of RC building structures, particularly in the context of applying capacity-based design and performance-based design approaches. These comparisons are detailed in Table 5 and Table 6.

On the other hand, the increase in bending moment for beam elements is less significant when accounting for vertical ground motion. This can be attributed to the fact that the structure being analyzed has a relatively short span.

Table 5. Contribution of vertical ground motion on the axial forces of column elements (axis F-5)

Story	COMB-1 (kN)	COMB-2 (kN)	Contribution of EQz	COMB-3 (kN)	COMB-4 (kN)	Contribution of EQz
	(1)	(2)	[(2)-(1)]/(2)	(3)	(4)	[(4)-(3)]/(4)
7th floor	706.8	1004.04	29.60%	797.37	1028.05	22.44%
4th floor	2651.89	3585.27	26.03%	2718.88	3617.78	24.85%
1st floor	4661.52	5989.84	22.18%	4765.92	6027.23	20.93%

Table 6. Contribution of vertical ground motion on the bending moment of beam elements (span 3-5, axis F)

Story	COMB-1 (kNm)	COMB-2 (kNm)	Contribution of EQz	COMB-3 (kNm)	COMB-4 (kNm)	Contribution of EQz
	(1)	(2)	[(2)-(1)]/(2)	(3)	(4)	[(4)-(3)]/(4)
7th floor	397.68	429.63	7.44%	853.05	875.67	2.58%
4th floor	659.61	692.34	4.73%	1828.43	1859.84	1.69%
1st floor	751.50	785.22	4.29%	2062.85	2080.45	0.85%

5. Conclusion

This study highlights the significant effects of vertical ground motion on the seismic responses of reinforced concrete structures, emphasizing the importance of a more comprehensive approach to seismic design. The analysis reveals that vertical accelerations can significantly affect internal forces, particularly axial forces in column elements, which are crucial for maintaining structural integrity. The findings suggest that conventional design methods, which focus mainly on horizontal loads, may be insufficient to ensure the seismic performance of RC buildings in seismically vulnerable areas.

Acknowledgement

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NGHIÊN CỨU ẢNH HƯỞNG CỦA THÀNH PHẦN GIA TỐC ĐỘNG ĐẤT THEO PHƯƠNG THẲNG ĐỨNG ĐẾN NỘI LỰC CỦA KẾT CẤU NHÀ BÊ TÔNG CỐT THÉP

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Tóm tắt: Bài báo nghiên cứu ảnh hưởng của thành phần gia tốc nền theo phương thẳng đứng đến phản ứng động đất của kết cấu bê tông cốt thép. Phương pháp tính toán thiết kế thực hành thường chủ yếu tập trung vào thành phần tải trọng động đất nằm ngang mà bỏ qua tác động đáng kể của gia tốc theo phương thẳng đứng. Nghiên cứu này tiến hành phân tích toàn diện hơn các đặc điểm của gia tốc nền theo phương thẳng đứng nhằm làm rõ kiến thức về dạng tải trọng này. Ví dụ phân tích số được tiến hành trên mô hình kết cấu nhà bê tông cốt thép nhiều tầng để đánh giá tác động của gia tốc động đất theo phương thẳng đứng đến nội lực, đặc biệt là lực dọc trong cột và mô men uốn trong dầm. Kết quả cho thấy, gia tốc nền theo phương thẳng đứng có thể làm tăng đáng kể nội lực kết cấu, đòi hỏi cần xem xét, kiểm tra trong công tác thiết kế hiện nay. Nghiên cứu này cũng nhấn mạnh tầm quan trọng của việc xem xét đến tác động giả gia tốc nền theo phương thẳng đứng trong công tác thiết kế kết cấu bê tông cốt thép nhằm đảo bảo an toàn cho công trình.

Từ khóa: *Phân tích động đất; phổ phản ứng gia tốc đàn hồi; gia tốc nền theo phương thẳng đứng; nhà bê tông cốt thép.*

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