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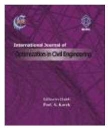

OPTIMIZATION PROBLEM IN COMPUTATION OF THE CRITICAL EARTHQUAKE TO EVALUATE THE SUFFICIENCY OF DISCONTINUITY JOINT BASED ON THE IRANIAN STANDARD NO. 2800

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ABSTRACT

Earthquakes are random phenomena and there has been no report of similar earthquakes occurring worldwide. Therefore, traditional methods of designing buildings based on past earthquakes with inappropriate discontinuity joints are sometimes ineffective for vital structures. This may lead to collision and destruction of adjacent structures during a severe earthquake. As in the Iranian Standard No. 2800-4, this distance should be at least five-thousandths of the building height from the base level to the adjacent ground boundary for buildings up to eight stories to prevent or reduce this damage. Also, for important or/with more than eight-story buildings, this value is determined using the maximum nonlinear lateral displacement of the structures by considering the effects of the P-delta. Also, if the properties of the adjacent building are not known, this distance should be considered at least equal to 70% of the maximum nonlinear lateral displacement of the structures. The main objective of this study is to investigate the adequacy of the discontinuity joint introduced in the Iranian Standard No. 2800-4 based on the critical excitation method. This method calculates critical earthquakes for three buildings (e.g., three-, seven- and eleven-story moment frames) by considering some constraints on the energy, peak ground acceleration, Fourier amplitude, and strong ground motion duration. The results indicate that the minimum gap between two adjacent buildings derived from the existing codes is lower than those calculated using the critical excitation method. Therefore, oscillation might occur if a structure is designed according to the seismic codes and subjected to a critical earthquake.

Keywords: Critical earthquake, discontinuity joint, nonlinear dynamic analysis, Iranian code No. 2800-4, metaheuristic optimization algorithm.

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1. INTRODUCTION

Seismic pounding between neighboring buildings is a significant concern in structural engineering, especially in earthquake-prone areas [1]. This issue happens when two buildings, which may react differently during seismic events, collide because they do not have enough space or separation. The consequences of seismic pounding can be severe, leading to structural damage, higher repair costs, and even catastrophic failures [1, 2]. Recent research has been dedicated to understanding how seismic pounding works, creating design guidelines, and finding ways to reduce its impact [1, 2]. Various studies have used advanced numerical simulations to analyze how adjacent buildings behave during earthquakes to delve deeper into this phenomenon. For example, using finite element analysis, Khatami *et al.* [2] utilized the rubber bumper to reduce the pounding effect between two adjacent isolated buildings. In essence, addressing the issue of seismic pounding is crucial for ensuring the safety and resilience of buildings in earthquake-prone regions. Ongoing research efforts are vital for improving design practices and developing innovative solutions that can effectively minimize the risks associated with this phenomenon. Santos *et al.* [3] studied a comparative analysis of various international seismic codes regarding their treatment of structural irregularities in elevation. They represented that these irregularities could enhance the seismic resilience of both new and existing buildings. Noman *et al.* [4] investigate the pounding effect for buildings with different heights in Pakistan, where these types of buildings are common. Therefore, pounding between these structures can lead to significant structural damage during earthquakes. From the above-mentioned sentences, the discontinuity joint is one of the most important aspects of building design to prevent damage and destruction caused by earthquakes. This distance between two adjacent buildings prevents them from colliding during an earthquake. Given the recent advances in earthquake engineering, new methods have been proposed to determine the discontinuity joint, which are more accurate and efficient than traditional methods [5].

Optimization is a mathematical discipline that focuses on finding the best solution from a set of feasible solutions, often subject to various constraints [6-8]. It is crucial in numerous fields, including engineering, economics, logistics, and operations research. The primary goal of optimization is to maximize or minimize a particular objective function [6-8], which can represent costs, profits, efficiency, or other measurable factors. There are different optimization methods to solve the problems [9-11]. Metaheuristic algorithms are a class of optimization techniques that provide approximate solutions to complex optimization problems, especially for nonlinear problems with linear or nonlinear constraints. They are particularly useful when traditional optimization methods are impractical due to the problem's size or complexity [6-8].

The critical excitation method is a significant approach in earthquake engineering. This method is particularly focused on enhancing structures' seismic resistance by identifying the most severe earthquake scenarios that a structure might face. Therefore, it can help engineers design buildings that can effectively withstand such conditions [12].

Takewaki *et al.* [13] focused on the unique characteristics of pulse-like ground motions that occur in near-field seismic events and their significant impacts on structural responses. They also investigated the effects of critical ground motion on the performance of inelastic single-

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degree-of-freedom structures during seismic events [13]. Recently, Kamgar and Rahgozar [14] utilized the critical excitation method to find the optimum location of the belt truss system in a tall building with a linear behavior. Khatibinia *et al.* [15] have also determined the optimal parameters of the tuned mass damper for a structure subjected to critical earthquakes.

This paper studies the minimum required gap for a concrete moment frame with nonlinear behavior subjected to a critical earthquake. For this purpose, three concrete moment frames with three, seven, and eleven stories have been selected here. These structures are modeled utilizing the OpenSees software. Then, the critical earthquake for each building is computed. Since the critical earthquake depends on the dynamic characteristics of the structures, the considered constraints, and ..., therefore, one critical earthquake is computed for each structure. Finally, the minimum seismic gap is determined for the structures, and this value is also computed based on different codes and compared together.

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2. CRITICAL EARTHQUAKE FOR THE NONLINEAR FRAME STRUCTURES

This section studies the required information to compute the critical earthquake for multiple degrees of freedom nonlinear structures. It is assumed that the ground motion can be shown by a product of the Fourier series and an envelope function as follows [14, 16]:

$$\ddot{u}_g(t) = B_0(\mathrm{e}^{-\beta_1 t} - \mathrm{e}^{-\beta_2 t})\sum_{i=1}^{N_f} R_i \cos(\omega_i t - \phi_i) \tag{1}$$

where the B_0, R_i, ϕ_i, ω_i $(i = 1,2,...,N_f)$, β_1, and β_2 represent a scaling constant, unknown amplitudes, unknown phase angles, some different frequencies between 0.1 to 25 *Hz*, which are selected to cover the frequency range in the ground acceleration, and two known parameters to apply the transient tendency seen in the ground motion, respectively. It was shown that it is better to select some frequencies similar to the natural frequencies of the structures [16]. Determination of R_i and ϕ_i parameters so that the maximum roof displacement occurs during the earthquake is the main aim of computing the critical earthquake in this paper. The total duration of the structure is considered to be 30 *sec*. The constants B_0, β_1, β_2, and N_f are also considered to be 2.17, 0.13, 0.5, and 60 respectively. This procedure has been handled here utilizing a metaheuristic optimization algorithm (i.e., Grey Wolf Optimization algorithm [17]). For this process, some earthquakes that had occurred before were selected first. For these earthquakes, some initial information should be computed as follows (see Table 1):

Table 1: The required information obtained from the occurred ground-motion records to compute the critical earthquake

Earthquake date	Comp.	PGA (m/s^2)	Energy* ($m / s^{1.5}$)	Site
Coalinga (05.02.1983)	360	2.82	2.69	Cantua Greek
	270	2.19	2.16	
Imperial Valley (10.15.1979)	S45W	2.68	2.31	Calexico fire
	N45W	1.98	2.16	
Mammoth Lakes (05.25.1980)	90	4.02	3.73	Convict Greek
	180	3.92	**4.02**	
Morgan Hill (04.24.1984)	240	3.06	2.33	Halls Valley
	150	1.53	1.65	
Parkfield (12.20.1994)	90	2.89	1.33	Parkfield fault
	360	3.80	1.74	
San Fernando (02.09.1971)	N21E	3.09	2.08	Castaic Old Ridge
	N69W	2.65	2.48	
Sar Pole Zahab	90	5.54	5.23	Sar Pole Zahab
	0	6.84	4.51	
Manjil	L	3.22	1.26	Manjil
	T	3.51	1.17	
Naghan	L	**8.08**	4.02	Naghan
	T	5.73	3.26	
Ahar Varzaghan	L	1.65	1.38	Khaje
	T	2.30	2.00	

*$E = \sqrt{\int_0^\infty \ddot{v}_g^2(t)\,dt}$ (similar to Arias 1970).

Based on Table 1, the maximum values of PGA (M_1), energy (E), and Fourier amplitude spectra for available accelerations are computed to obtain the constraints in the optimization process. In addition, based on the Iranian Standard No. 2800-4 [18], the strong ground motion duration of the critical earthquake T^* (computed based on Trifunac and Brady [19]) has been considered to be more than 10 *sec*.

$$\sqrt{\int_0^{T^*} \ddot{u}_g^2(t)dt} \le E, \qquad\qquad (2)$$
$$max\left|\ddot{u}_g(t)\right| \le M_1; \qquad T^* \ge 10\,(sec).$$

In Eq. (2), the quantities E, and M_1 are computed as follows. It is assumed that we have selected a set of N earthquake records represented by $\ddot{v}_{gi}(t)$; $i = 1,2,...,N_r$. For the two parameters of E and M_1, the largest values of energy and peak ground acceleration are

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selected from Table 1 [16]:

The objective function is to maximize the roof displacement value. For this purpose, three concrete frames with three, seven, and eleven stories have been studied here. All structures are modeled nonlinearly with a concentrated plasticity model as two-dimensional frame buildings. A nonlinear time history analysis is performed utilizing the OpenSees software. Therefore, the critical excitation can be computed based on the above-assumed constraints on the ground motion.

3. OPTIMIZATION PROBLEM FOR COMPUTING CRITICAL EXCITATION

This paper aims to find the optimal unknown parameters of Eq. (1) to compute the critical excitation so that the maximum roof displacement occurs. This procedure can help the designer select an adequate seismic gap to avoid the pounding force between two adjacent buildings. This section states the objective function and constraint used in the optimization problem.

$$\begin{aligned} &\text{Find:} && R_i, \phi_i \\ &\text{Maximize:} && \text{maximum Roof Displacement Value} \\ &\text{Subjected to:} && R_i^{\min} \le R_i \le R_i^{\max} \\ &&& \phi_i^{\min} \le \phi_i \le \phi_i^{\max} \\ &&& \sqrt{\int_0^T \ddot{u}_g^2(t)dt} \le E \\ &&& \max\left|\ddot{u}_g(t)\right| \le M_1 \qquad T^* \ge 10\,(sec) \end{aligned} \tag{3}$$

where $R_i^{\min}$, $R_i^{\max}$, $\phi_i^{\min}$ and $\phi_i^{\max}$ are the lower and upper bounds of the two unknown parameters, respectively.

4. GREY WOLF OPTIMIZATION (GWO) ALGORITHM

GWO algorithm is categorized as a metaheuristic optimization algorithm inspired by grey wolf hunting. This method consists of three main hunting steps (i.e., search, siege, and attack) done by four wolf grey entitled *α, β, δ*, and *ω* [17]. This paper considers this algorithm to find the optimum parameters of two unknown parameters to compute the critical excitation. Detailed information about this algorithm can be found in Refs. [17].

5. CONCRETE MOMENT FRAME BUILDINGS

5.1. Properties of the studied models

In this section, the properties of the concrete moment frames are reported. These buildings are two-dimensional. All stories have 500 (kg/m^2) dead load except for the roof. This value

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is 300 (*kg/m²*) for the roof. Also, the live load value is 200 (*kg/m²*) for all stories except for the roof. This value is 150 (*kg/m²*) for the roof. Three concrete moment frames with three, seven, and eleven stories are considered here. Three frames have three spans and different stories. All buildings have similar story height (3 meters) and length span (5 meters). The specific weight of the concrete is 2500 (*kg/m³*). The concrete's specific compressive strength and young modulus are 25 (MPa) and 23500 (MPa), respectively. All beams and column sections for the three-story buildings are the same, and the rectangular sections for the beams and column elements are 400×400 mm^2 (with $5\phi 20$) and 450×450 mm^2 (with $12\phi 20$), respectively.

The seven-story concrete moment frame consists of twelve columns (500×500 mm^2 with $16\phi 20$) and nine beams (500×500 mm^2 with $5\phi 20$) for the first, second, and third stories. For the other stories, it has twelve beams (450×450 mm^2 with $5\phi 20$) and sixteen columns (450×450 mm^2 with $16\phi 20$).

The eleven-story concrete moment frame consists of sixteen columns (550×550 mm^2 with $16\phi 20$) and twelve beams (550×550 mm^2 with $6\phi 20$) for the first four stories. For stories 5-8, the eleven concrete moment frame has twelve beams (500×500 mm^2 with $6\phi 20$) and sixteen columns (500×500 mm^2 *with* $12\phi 20$). For the other stories, the eleven concrete moment frame has nine beams (450×450 mm^2 with $5\phi 20$) and twelve columns (450×450 mm^2 with $12\phi 20$). All rebars are assumed to be S400. The cover for the rebars is considered to be 50 (*mm*). It should be noted that the damping matrix has been constructed based on the Rayleigh damping method for a damping ratio (ξ) of 0.05 as follows [20]:

$$\begin{aligned} [C] &= \alpha[M] + \beta[K] \\ \alpha &= 2\xi \frac{\omega_1\omega_2}{\omega_1+\omega_2} \\ \beta &= \xi \frac{2}{\omega_1+\omega_2} \end{aligned} \tag{4}$$

where [M], [K], [C], ω_1 and ω_2 are the mass matrix, the stiffness matrix, the damping matrix, the first natural frequency, and the second natural frequency of the building, respectively. The first two natural periods of the studied buildings are shown in Table 2.

Table 2: The first two natural periods of the studied moment frames

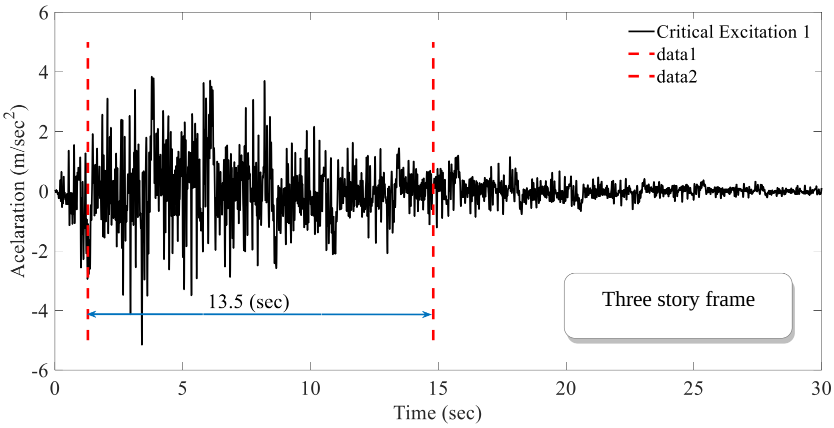
Number of Stories	The first two natural period of the structure (*sec*)
Three	0.7064
	0.2255
Seven	1.3846
	0.4925
Eleven	1.9131
	0.7000

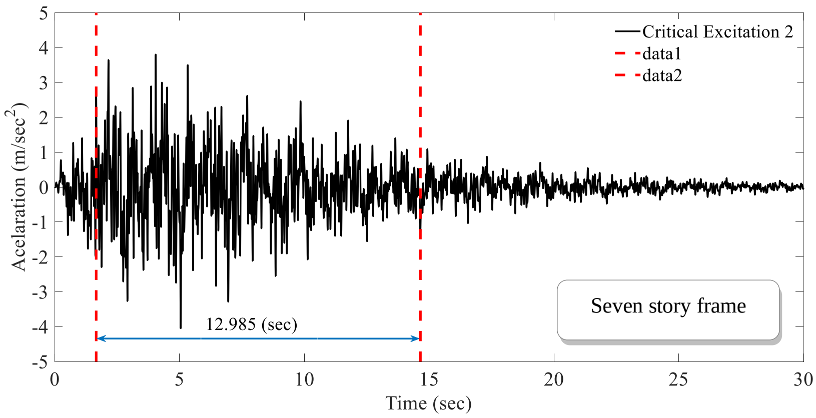
6. RESULTS AND DISCUSSION

This section describes the critical excitation computed for three concrete moment frames and their properties. Table 3 shows the properties of computed critical excitation, such as PGA, Arias intensity, duration of strong ground motion, and the maximum value of roof displacement. Also, Fig. 1 depicts the acceleration time history as well as the Fourier spectra for the computed critical accelerations.

Table 3: The properties of critical excitations

Number of stories	PGA (m/sec^2)	Arias Intensity ($m/sec^{1.5}$)	Duration of strong ground motion (sec)	Housner Intensity (m)	Predominant Period (sec)	Max. roof Disp. (m)
Three	5.15	4.21	13.52	1.51	0.04	0.1239
Seven	4.05	3.71	12.985	1.41	0.10	0.1979
Eleven	4.42	4.015	13.46	1.42	0.06	0.4870





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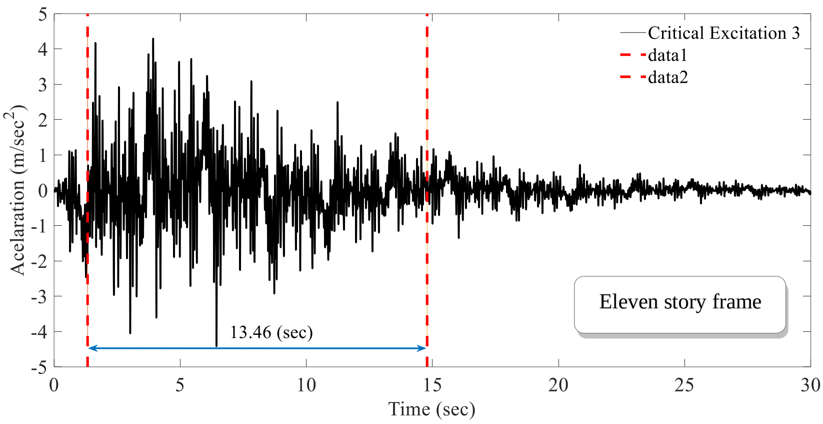

Figure 1: The acceleration time history for critical excitations for different concrete moment frames

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Many codes propose the minimum required distance between two adjacent buildings to avoid the pounding effect during severe earthquakes (e.g., [21-26]). ASCE 2007 [21] and IBC [23] propose the following equation for computing the minimum required distance between two adjacent buildings (δ_M) to avoid the pounding effects:

$$\delta_M = \frac{C_d \delta_{\max}}{I} \quad (5)$$

In Eq. (5), C_d , $\delta_{\max}$ and I depict the deflection amplification factor, the maximum elastic story displacement and the important factor, respectively. NBC Peru E030 [25] proposes that the minimum gap between adjacent buildings (δ_M) should be more than (2/3) of the sum of the maximum story displacement of adjacent buildings. This value should be more than $3+0.004(h-500)$, in which, in this equation, *h* is the structure's height in unit *cm*.

The minimum sufficient gap between two adjacent buildings in Australi when the structure height is more than 15 (*m*) is 1% of the structure’s height [27]. In Canada, adjacent buildings must be built within sufficient gap from each other based on the summation of the maximum elastic story displacement of the structure [28]. In Greece, the gap between adjacent buildings is determined as follows based on the number of stories with potential contact above the ground motion [29]:

1- 4 (*cm*) for the first three stories
2- 8 (*cm*) for four to eight stories
3- 10 (*cm*) for more than eight stories

In India, when the adjacent buildings have floors at different elevations, the required minimum gap is more significant to accommodate the relative movements during an earthquake. This gap is given by [30]:

$$Minimum\ gap = R \times \left(Summation\ of\ Story\ Displacement \right) \quad (6)$$

However, when the story levels of two adjacent buildings are the same in elevation, the relative movement is reduced, and the value of *R* is halved. Thus, the formula becomes [30]:

$$Minimum\,gap = \frac{R}{2} \times \left(Summation\,of\ Story\,Displacement \right) \qquad (7)$$

In Serbia, building regulations specify that the minimum separation gap between two adjacent structures should be 3 (*cm*). This base gap must be increased by 1 (*cm*) for every 3 meters high above 5 meters. This guideline helps ensure that taller buildings have adequate separation to accommodate movements and prevent damage during seismic events [31]. In Turkey, regulations mandate that the minimum separation gap between two adjacent buildings is 3 (*cm*) for structures up to 6 (*m*) in height. For every additional 3 (*m*) in height, this gap must be increased by 1 (*cm*) [32].

The three concrete moment frames described in section 5 are considered here. It is assumed that they are special moment frames. These structures are excited by the earthquake reported in Table 1 and the computed critical excitations. Therefore, the maximum displacement of stories was computed based on the different earthquakes. After that, the minimum required gap for the structures from the building boundary is determined to show the ability of the critical excitation method.

Table 4 shows the maximum roof displacement values of concrete special moment frames subjected to the different earthquake loads. Also, Table 5 compares different codes in calculating the minimum required gap between two adjacent buildings for different structures subjected to different earthquakes. It is assumed that the buildings are residential and their coefficient of behavior against the earthquake equals 7.5. Therefore, the magnification factor of the lateral displacement of the building is equal to 5.5. It is also assumed that the characteristics of the adjacent building are unknown; therefore, the values obtained for the known building are also used for the adjacent building. Finally, it is assumed that the maximum value of roof displacement for all of the studied earthquakes is considered when the structure's maximum linear or nonlinear displacement is required.

Table 4: The maximum roof displacement values

Earthquake (component)	**Maximum roof displacement (*m*)**		
	Three story building	Seven story building	Eleven story building
Coalinga (360, 270)	**0.1053**, 0.0697	0.0880, 0.1572	0.1231, 0.1670
Imperial Valley (S45W, N45W)	0.0712, 0.0379	0.0765, 0.1473	0.1108, 0.1374
Mammoth Lakes (180, 90)	0.0626, 0.0910	0.1139, 0.1489	0.2108, 0.1949
Morgan Hill (240, 150)	0.1026, 0.0654	**0.1719**, 0.0754	0.1892, 0.0712
Parkfield (90, 360)	0.0224, 0.0284	0.0253, 0.0240	0.0233, 0.0269
San Fernando (N21E, N69W)	0.0416, 0.0757	0.0704, 0.1027	0.0817, 0.1161
Sar Pole Zahab (90, 360)	0.1018, 0.0749	0.1501, 0.1916	0.2185, **0.3138**
Manjil (L, T)	0.0439, 0.0357	0.0719, 0.0626	0.1613, 0.1483

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Naghan	0.0890, 0.0866	0.1422, 0.1159	0.2755, 0.1279
Ahar Varzaghan (L, T)	0.0232, 0.0331	0.0533, 0.0657	0.0626, 0.1204
Critical Excitation 1	**0.1239**	-	-
Critical Excitation 2	-	**0.1979**	-
Critical Excitation 3	-	-	**0.4870**

Table 5: The minimum required gap between two adjacent buildings

Codes	**Minimum required seismic gap between two adjacent buildings (c*m*)**		
	Three story building	Seven story building	Eleven story building
Standard No. 2800-4	9	21	43.932
NBC Peru E03	4.6	9.4	14.2
Australia	-	21	33
Canada	3.83	6.25	11.41
Greece	4	8	10
Serbia	4.33	8.33	12.33
Turkey	4	8	12
Critical excitation 1	**24.78**	-	-
Critical excitation 2	-	**39.58**	-
Critical excitation 3	-	-	**97.4**

It should be noted that the minimum required gap between two adjacent buildings based on the critical excitation method is computed from the dynamic properties of the structures. Therefore, the minimum required gap between two adjacent buildings is computed for the worst excitation load applied to the structure. Therefore, the minimum distance calculated by the critical excitation method will be more reliable. Based on Tables 4-5, it can be concluded that the calculated values based on the existing codes are less than the calculated value by the critical excitation method. Therefore, if the studied structure is subjected to a critical earthquake, the pounding effect will be experienced if the seismic gap distance is selected based on the seismic code. Therefore, the critical excitation method can determine the minimum required gap from the building boundary to eliminate the pounding effects in regions where severe earthquakes occur.

The following observation has been made based on the numerical results: This method can determine the minimum required gap between two adjacent buildings to prevent pounding effects in regions prone to severe earthquakes. The sum of the maximum story displacements for both buildings at each level indicates the minimum required separation distance. The adjacent buildings are assumed to have different properties and may oscillate in different phases. Consequently, the minimum required gap between two buildings can be estimated by summing the maximum story displacements for both structures at each story level during critical earthquakes. It has been demonstrated that the values calculated using existing codes are less than those derived from the critical excitation method. As a result, if a structure is designed according to existing codes and experiences a critical earthquake, pounding may occur. This method can be applied to any structure from a practical point of view. For structures with different dynamic properties, the minimum required distance can be determined at any desired

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height by summing the maximum story displacements of adjacent buildings at the same level. It is important to note that the critical excitation method cannot provide a unique formula for all situations and structures. Although this method is time-consuming, it is highly effective and should be considered for important structures.

7. CONCLUSION

This study employed the critical excitation method to determine the minimum necessary gap between two adjacent buildings. For this purpose, critical earthquakes were calculated using a metaheuristic optimization algorithm, such as GWO, based on available data. Three concrete moment frames were analyzed and modelled using OpenSees software. The critical excitations were then calculated by setting constraints on the ground motion to maximize roof displacement. Furthermore, the characteristics of the earthquake and the structure play crucial roles in determining the minimum gap needed to prevent pounding effects between adjacent buildings. Consequently, this gap may vary depending on the specific earthquake. The critical earthquake method effectively generates a critical earthquake tailored to the structure's properties and constraints. Thus, this study uses the critical excitation method to compute the minimum gap required between adjacent buildings. The numerical results indicate that the values derived from the existing codes are lower than those calculated using the critical excitation method. Therefore, oscillation might occur if a structure is designed according to the seismic codes and subjected to a critical earthquake.

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