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Research Article

Verification of Formulas for Periods of Adjacent Buildings Used to Assess Minimum Separation Gap Preventing Structural Pounding during Earthquakes

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Insufficient separation distance between adjacent buildings may lead to serious damages during earthquakes due to structural pounding. The best way to prevent collisions is to provide sufficiently large separation distance between structures. In this paper, the periods of two closely spaced linear and nonlinear buildings have been investigated so as to accurately assess the minimum in-between separation gap. A new equation to calculate the effective periods of inelastic buildings has been proposed, and its effectiveness has been verified through numerical analysis. The results of the investigation conducted for inelastic buildings with different number of stories indicate that the proposed formula allows us to prevent earthquake-induced structural pounding by ensuring an adequate value of seismic gap.

1. Introduction

It is obviously seen that insufficient separation distance between closely spaced buildings or bridge segments may provide serious damages under seismic excitations due to structural collisions [1, 2]. This phenomenon, called as structural pounding, occurs when the gap size between structures is not large enough so as to accommodate their relative movements [3]. In order to investigate the earthquake-induced pounding between buildings, many researchers have studied the problem both experimentally and numerically ([4–7], for example). It is quite obvious that a best way to prevent collisions is to provide sufficiently large separation distance between structures. On the contrary, because of land shortage and high prices of lands in many places, providing too large space is an undesired solution from the economical point of view. The precise estimation of the minimum gap size to prevent pounding of buildings during different earthquakes is not an easy task. The building codes suggest calculating the in-between seismic gap by using relatively simple formulae (for example, [8]). More detailed equations have also been proposed by a number of researchers. Kiureghian [9] suggested an equation to calculate separation distance based on structural vibration periods and damping ratios of buildings. Jeng et al. [10] proposed the spectral difference method based on random vibration theory that considers the first-mode approximation for displacements of elastic multistory buildings. Filatrault et al. [11] improved an equation for calculating the separation distance by adding the effect of a structural damping ratio. Penzien [12] and Kasai et al. [13] recommended methods for calculating effective periods of inelastic buildings. Although a number of different formulae have been proposed and analyzed for both elastic and inelastic buildings, their effectiveness is still not fully satisfactory [14]. Therefore, the aim of the present paper is to propose and verify the effectiveness of a new equation to calculate the effective periods of inelastic buildings, based on ductility demand, which can be successfully applied for the determination of the minimum separation gap.

2. Methods for Calculating Critical Distance

Different formulae have been considered in order to determine the minimum separation distance between two adjacent buildings so as to prevent their pounding during earthquakes. The absolute sum method (ABS) and the square root of the sum of the squares (SRSS) are the most basic approaches, and thus they are often used in the seismic codes ([8], for example). The methods are described by the following equations, respectively:

$$S = \delta_i + \delta_j, \tag{1}$$

$$S = \sqrt{\delta_i^2 + \delta_j^2}, \tag{2}$$

where S is the minimum gap size between buildings, while δ_i and δ_j denote peak lateral displacement of a building i and j, respectively.

Some codes also take into account height of two adjacent buildings, h_i and h_j, and then, the minimum separation distance is described as follows [15]:

$$S = 0.05\left(h_i + h_j\right). \tag{3}$$

Jeng et al. [10] suggested a new equation based on the SRSS formula:

$$S = \sqrt{\delta_i^2 + \delta_j^2 - 2\rho_{\mathrm{op}}\delta_i\delta_j}, \tag{4}$$

where ρ_{op} is the cross correlation coefficient reflecting the vibration phase between two elastic buildings, which can be determined as [10]

$$\rho_{\mathrm{op}} = \frac{8\sqrt{\zeta_i\zeta_j}\left(\zeta_j + \zeta_i\left(T_j/T_i\right)\right)\left(T_j/T_i\right)^{3/2}}{\left(1-\left(T_j/T_i\right)^2\right)^2 + 4\zeta_i\zeta_j\left(1+\left(T_j/T_i\right)^2\right)\left(T_j/T_i\right) + 4\left(\zeta_i^2+\zeta_j^2\right)\left(T_j/T_i\right)^2}, \tag{5}$$

where T_i and T_j are the vibration periods of buildings i and j, respectively, while ζ_i and ζ_j denote the structural damping ratios.

Based on the results of investigation focused on a cyclic process by using different values of periods of buildings, Naderpour et al. [16] suggested to use another expression for the cross-correlation coefficient, ρ_{op}, which can be written in a more general form as

$$\rho_{\mathrm{op}} = \left|\frac{T_j}{T_i} - 10.5\left(T_j - T_i\right)\right|. \tag{6}$$

On the contrary, Penzien [12] parametrically investigated the effectiveness of properties of inelastic buildings under earthquake excitations and suggested that, in the case of such structures, the values of the effective periods, T_{ni} and T_{nj}, and the effective damping ratios, ζ_{ni} and ζ_{nj}, should be rather applied in equation (5) instead of T_i and T_j and ζ_i and ζ_j. He proposed the following formulae (substitution of subscripts i by j gives the corresponding expressions for T_{nj} and ζ_{nj}):

$$T_{ni} = T_i\phi_i, \tag{7}$$

$$\zeta_{ni} = \zeta_i + \overline{\zeta}_i, \tag{8}$$

where [12]

$$\phi_i = \sqrt{\frac{\mu_i}{\gamma + \beta_i\left(\mu_i - \gamma\right)}}, \tag{9}$$

$$\overline{\zeta}_i = \frac{2}{\pi}\cdot\frac{\left(\mu_i-\gamma\right)\left(1-\beta_i\right)\gamma}{\mu_i\left(\gamma+\beta_i\left(\mu_i-\gamma\right)\right)}, \tag{10}$$

where μ_i is the ductility demand, γ is the constant value ($\gamma = 1.54$ [12]), and β_i stands for the ratio between the ultimate stiffness and the initial stiffness.

The nonlinear behavior of adjacent structures was also studied by Kasai et al. [13]. They suggested to modify equations (9) and (10) to have

$$\phi_i = \left(1 + 0.18\left(\mu_i - 1\right)\right), \tag{11}$$

$$\overline{\zeta}_i = 0.16\left(\mu_i - 1\right)^{0.9}. \tag{12}$$

3. Proposed Formula for Effective Period of Inelastic Building

Another approach to determine the effective vibration periods of inelastic structures is proposed in this paper. The extensive numerical analysis has been conducted for six inelastic lumped mass models of buildings with different number of stories (see Table 1 for details concerning their natural vibration periods) using the computer program *CRVK* (written at the *FEUP* and described in detail in [16]). The program allows us to calculate the lateral displacements, velocities, accelerations, dissipated energies, etc. Considering six assumed lumped mass numerical models, the periods of buildings were estimated and used as the main input to analyze and investigate the effective structural periods of inelastic structures. This was obtained under the assumption of equal height and mass of all stories of both structures, apart from the detailed geometrical properties of buildings, since all possible geometrical configurations are allowed. Moreover, the values of lumped masses and stiffness were variable so as to analyze different cases. In total, more than

Table 1: Natural vibration periods of the six buildings studied.

Model	One-story	Two-story	Three-story	Four-story	Five-story	Six-story
Period (s)	0.1140	0.1917	0.2598	0.3224	0.3811	0.4888

1000 lumped mass models have been considered in the study. The representative examples of the force-displacement curves of analyzed inelastic buildings with different number of stories are presented in Figure 1. As it can be seen from the figure, the peak forces in building are equal to 2.6×10^4 kN, 6.1×10^4 kN, 7.4×10^4 kN, 9.7×10^4 kN, 11.02×10^4 kN, and 11.4×10^4 kN for the one-story, two-story, three-story, four-story, five-story, and six-story buildings, respectively. The results indicate that the increase in the structural period (due to bigger number of stories) results in larger peak forces. For instance, the five-story building has a natural period of 0.3811 s, which is 3.34 times larger than the period of one-story building, and, subsequently, the peak force for the five-story building is 4.24 times larger than the peak force for the one-story structure. The plots also show a logical trend to calculate an effective period based on the ductility demand in the case of nonlinear structural behavior. Reducing the stiffness naturally causes the increase in displacements and period of building. Based on the results obtained, the following equation is suggested, so as to calculate the nonlinear effective period of i-th structure:

$$T_{ni} = T_i (1 + \alpha_i), \tag{13}$$

where α_i is the increased period ratio which is obtained as

$$\alpha_i = \eta_i \left(\mu_i^{0.385} - 1\right), \tag{14}$$

where η_i is the increasing factor $(0.94 \le \eta_i \le 0.98)$.

4. Verification of Effectiveness of Different Methods

A series of two adjacent buildings with different number of stories have been analyzed so as to investigate numerically the critical distance between them under different earthquakes. The relative periods, lateral displacements, and ductility of lumped mass models in different situations have been evaluated in order to compare the separation distances and to estimate the minimum gap size. The representative examples of the results for the Kobe earthquake of 1995, Loma Prieta earthquake of 1989, and Parkfield earthquake of 1966 are shown in this paper.

4.1. Elastic Buildings. The analysis for the elastic buildings has been firstly conducted. The ABS and SRSS methods (equations (1) and (2)) as well as the formulations proposed by Jeng et al. [10] and Naderpour et al. [16] (equations (4)–(6)) have been considered. The results of the analysis showing the relation between the calculated required separation distance and the ratio between the periods of elastic structures are presented in Figure 2. Additionally, the examples of the lateral displacement-time histories for the third stories of the elastic three-story building and the seven-story building are shown in Figure 3. The period and damping ratio for the first structure are equal to $T_i = 0.2598$ s and $\zeta_i = 0.05$, and the peak displacements of its third story δ_i

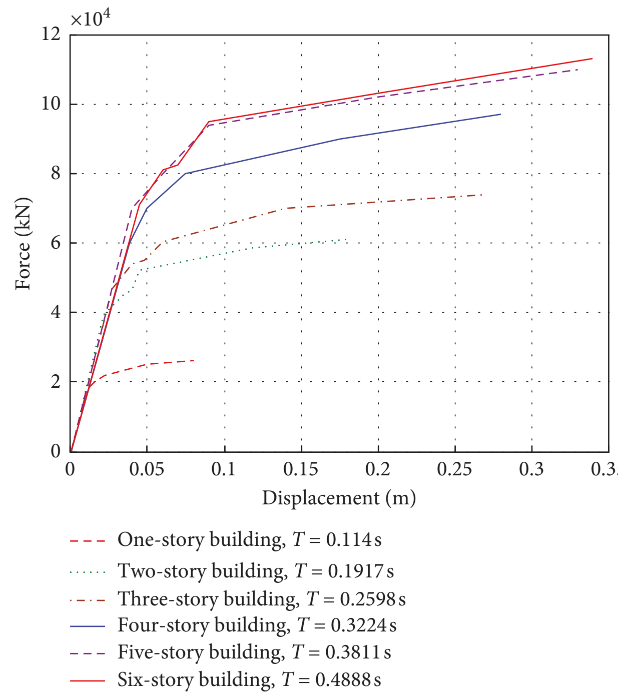


Figure 1: Force-displacement curves of the six inelastic buildings.

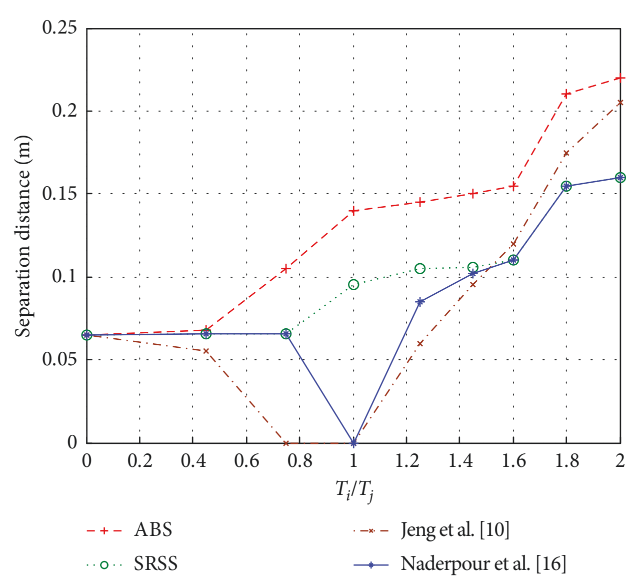
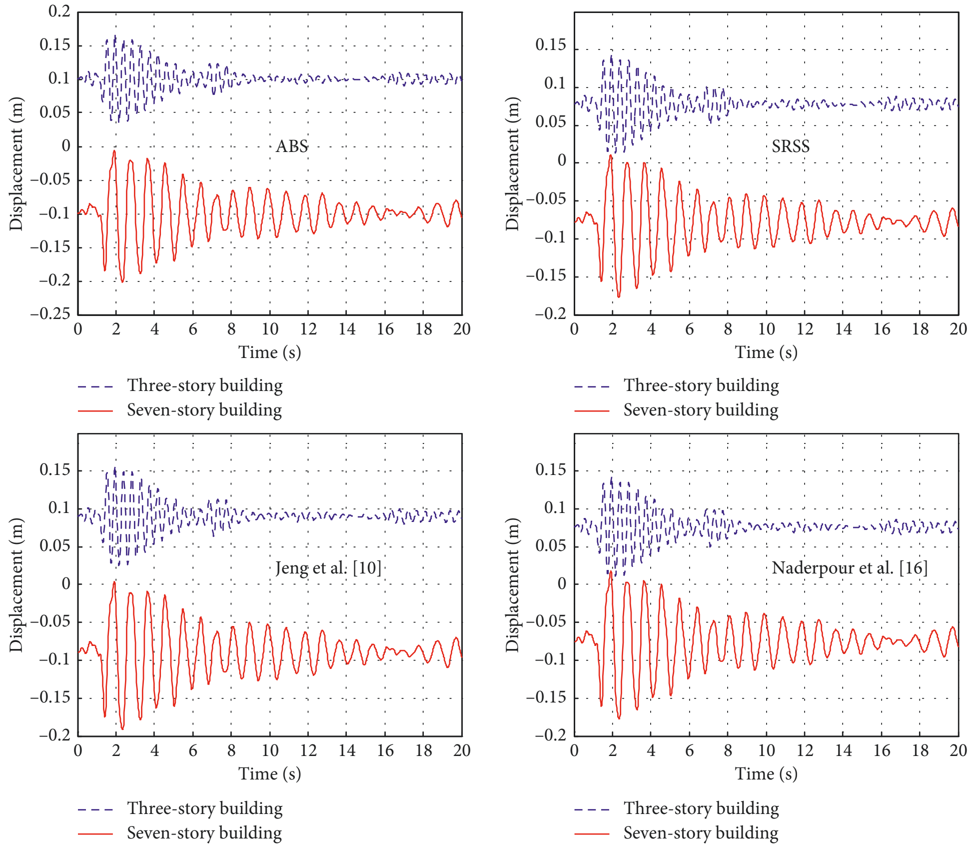
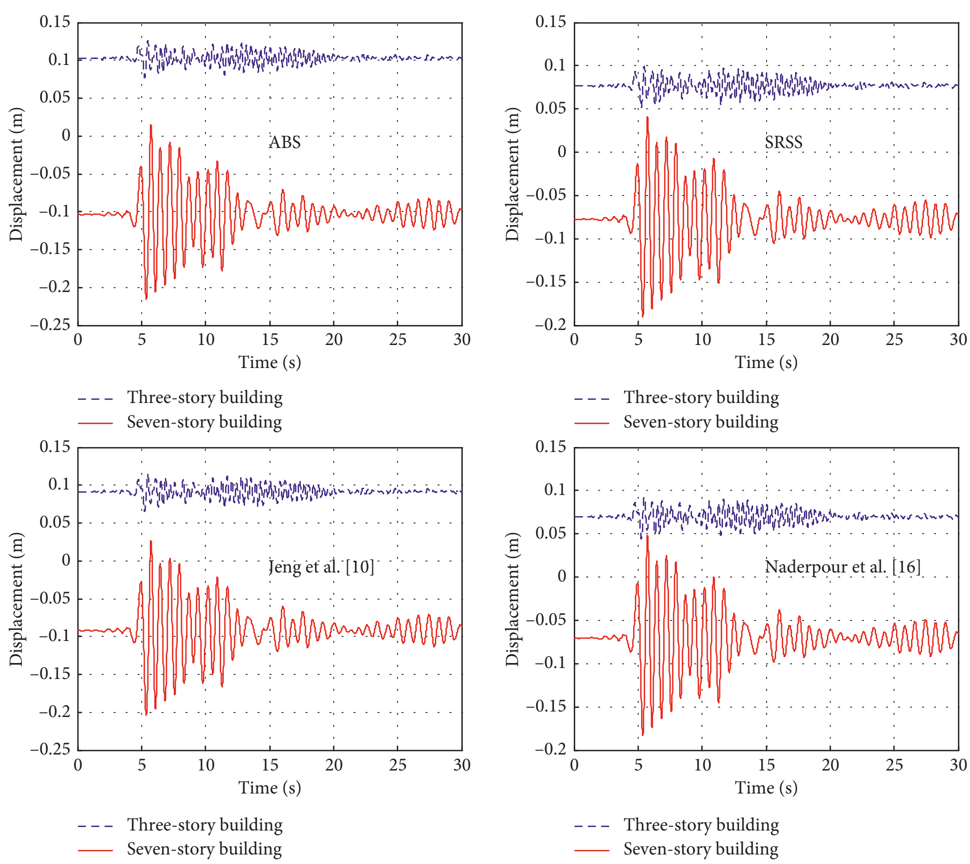


Figure 2: Minimum separation distance vs. ratio between periods of elastic buildings.

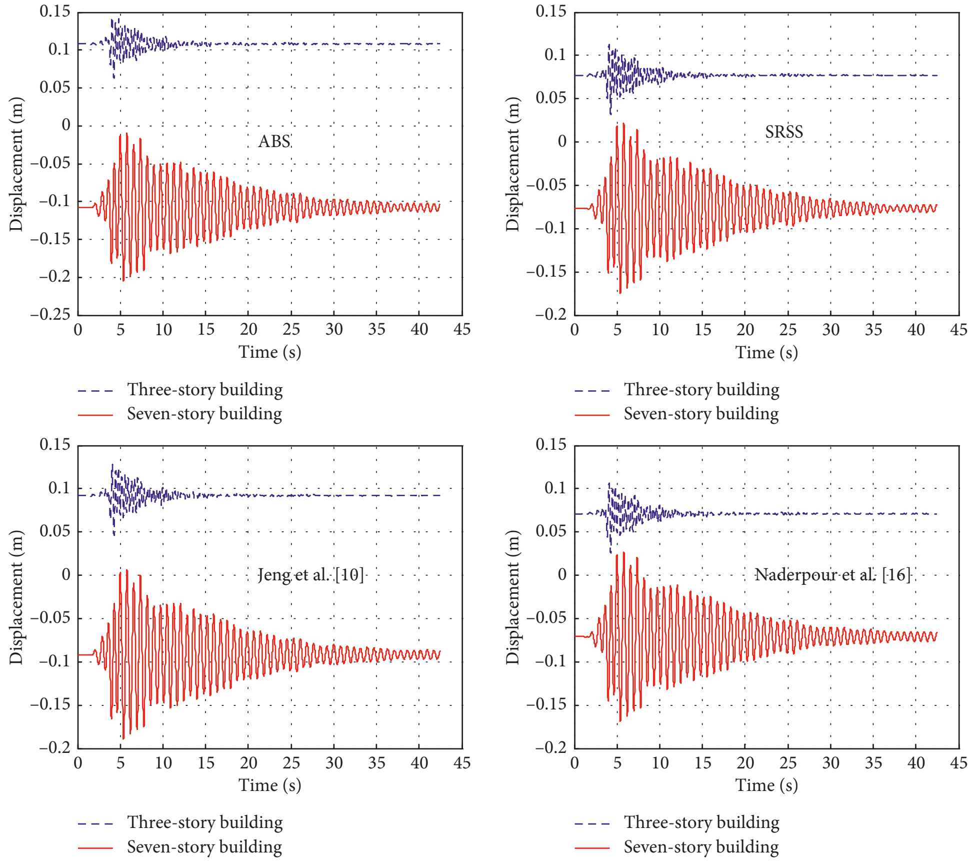


(a)



(b)

Figure 3: Continued.



(c)

Figure 3: The lateral displacements of two buildings with gap size calculated by different methods for different earthquake records (elastic buildings). (a) Kobe earthquake. (b) Loma Prieta earthquake. (c) Parkfield earthquake.

under the Kobe, Loma Prieta, and Parkfield earthquake are 0.0610 m, 0.0225 m and 0.0359 m, respectively. On the contrary, the period and damping ratio for the second structure are equal to $T_j = 0.4905$ s and $\zeta_j = 0.05$, and the peak displacements of its third story δ_j under the Kobe, Loma Prieta and Parkfield earthquake are 0.1057 m, 0.1184 m, and 0.0983 m, respectively. For this case of arrangement involving the elastic three-story and seven-story buildings, the following minimum separation distance, S, has been calculated using different formulae (Figure 2):

$$\frac{T_j}{T_i} = 1.881 \xrightarrow{\text{Figure}(2)} \begin{cases} \text{ABS} \longrightarrow S = 0.2059\,\text{m}, \\ \text{SRSS} \longrightarrow S = 0.1542\,\text{m}, \\ \text{Jeng et al. [10]} \longrightarrow S = 0.1837\,\text{m}, \\ \text{Naderpour et al. [16]} \longrightarrow S = 0.1528\,\text{m}. \end{cases} \tag{15}$$

It can be seen from Figure 3 that using all analyzed methods has allowed us to prevent collisions during the time of each earthquake. It should be underlined, however, that the ABS and Jeng et al. [10] formulations can be difficult to be accepted in many cases due to economical aspects since they propose the gap size much larger than the required minimum separation distance. On the contrary, the application of the SRSS and Naderpour et al. [16] formulae has resulted in the optimal gap size value.

4.2. Inelastic Buildings. In the second stage of the analysis, the investigation for the inelastic buildings has been carried out. The formulations by Penzien [12] and Kasai et al. [13] (equations (7)–(12)), together with the equation proposed in this paper (equation (13)), have been considered. The examples of the results of the analysis showing the relation between the calculated required separation distance and the ratio between the effective periods of structures for $\mu_i = 2$ are presented in Figure 4. Additionally, similarly as for the linear behavior, the examples of the lateral displacement time histories of the third stories of the inelastic three-story building ($\zeta_i = 0.05$) and the seven-story building ($\zeta_j = 0.05$) are shown in Figure 5. The effective periods for the first structure calculated by three different equations are equal to $T_{ni} = 0.2998$ s, $T_{ni} = 0.2896$ s, and $T_{ni} = 0.357$ s, respectively. The effective periods for the second structure calculated by three different equations are equal to $T_{nj} = 0.5561$ s, $T_{nj} = 0.5289$ s, and $T_{nj} = 0.6722$ s, respectively. For this case of arrangement involving these two inelastic structures, the following minimum separation distance, S, has been calculated using different formulae (Figure 4):

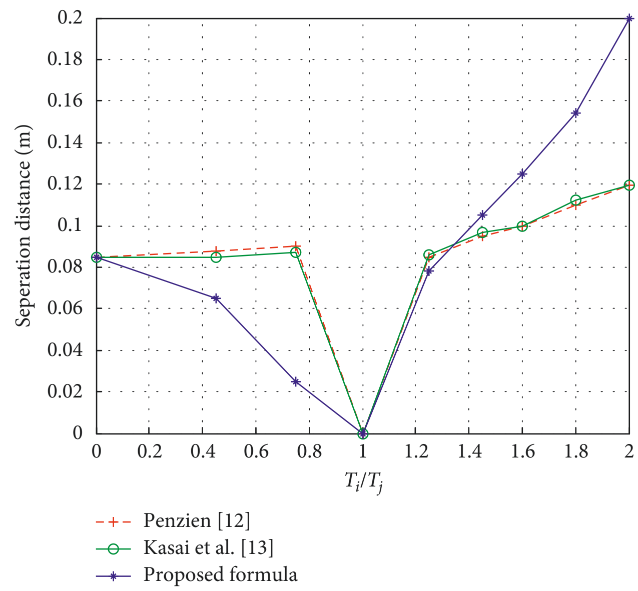
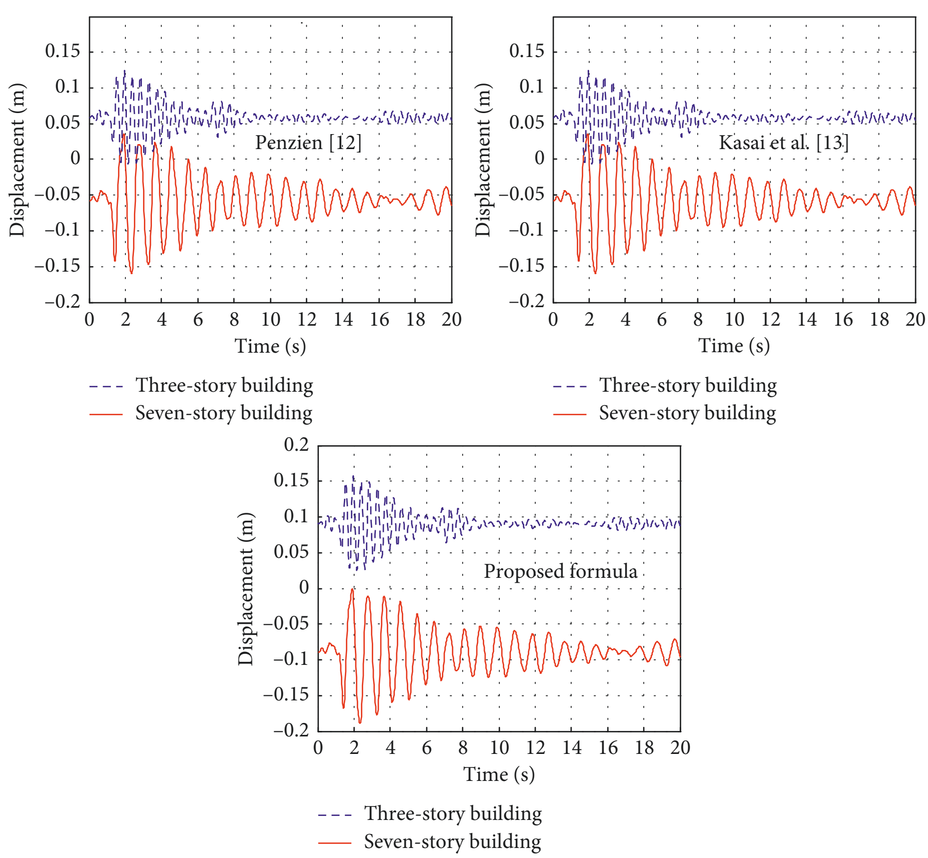
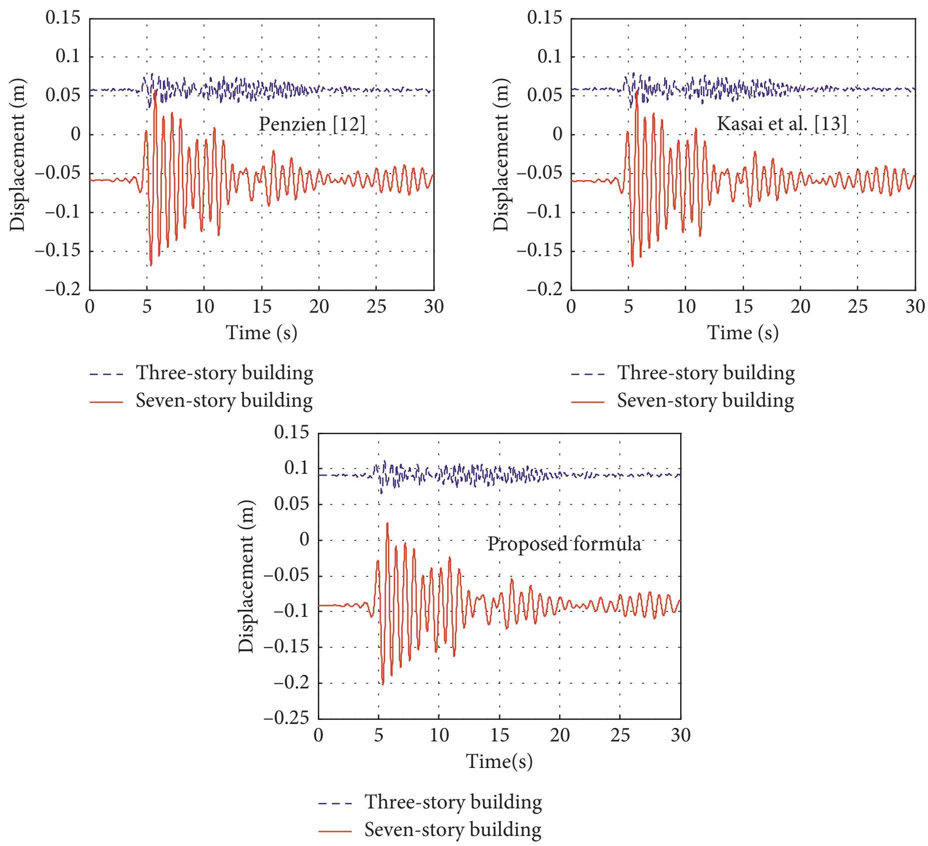


FIGURE 4: Minimum separation distance vs. ratio between effective periods of inelastic buildings.

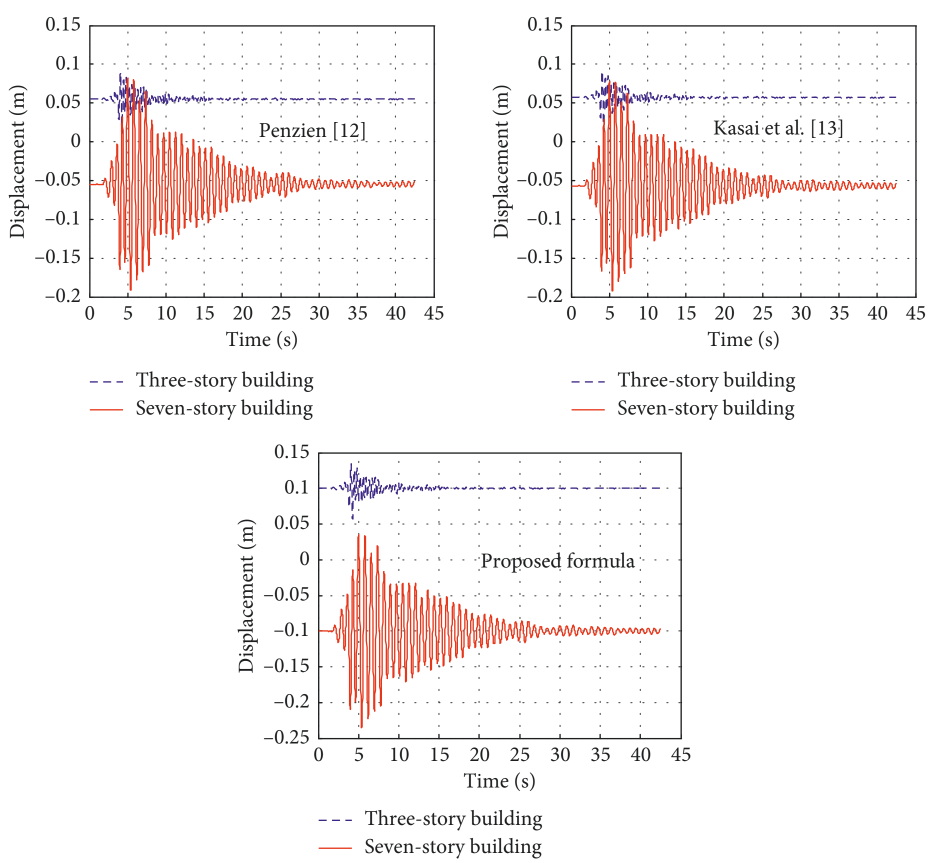


(a)

FIGURE 5: Continued.



(b)



(c)

Figure 5: The lateral displacements of two buildings with gap size calculated by different methods for different earthquake records (inelastic buildings). (a) Kobe earthquake. (b) Loma Prieta earthquake. (c) Parkfield earthquake.

$$\begin{cases} \text{Penzien [12]} \longrightarrow \dfrac{T_{nj}}{T_{ni}} = 1.855, \\ \text{Kasai et al. [13]} \longrightarrow \dfrac{T_{nj}}{T_{ni}} = 1.826, \\ \text{proposed formula} \longrightarrow \dfrac{T_{nj}}{T_{ni}} = 1.883, \end{cases} \xrightarrow{\text{Figure}(4)} \begin{cases} S = 0.1163\,\text{m}, \\ S = 0.1183\,\text{m}, \\ S = 0.1943\,\text{m}. \end{cases} \tag{16}$$

It can be seen from Figure 5 that using the formulations by Penzien [12] and Kasai et al. [13] has resulted in collisions during the time of each earthquake. It is therefore demonstrated that the separation distances calculated by the above two approaches is not able to accommodate the relative displacements. On the contrary, the application of the proposed equation (equation (13)) has allowed us to prevent earthquake-induced structural pounding for all ground motions by ensuring the appropriate seismic gap. It should be added that the occurrence of a partial mechanism of collapse for inelastic buildings leads to the decrease in the stiffness of structures and, therefore, the periods of buildings are naturally increased. This leads to the increase in lateral displacements and, consequently, results in larger minimum separation distance required to prevent structural collisions during ground motions.

5. Conclusions

In this paper, the periods of two adjacent buildings have been investigated so as to accurately assess the minimum separation gap preventing structural pounding during earthquakes. Both linear and nonlinear structural behaviors under seismic excitations have been considered. Focusing on ductility, a new equation to calculate the effective periods of inelastic buildings has been proposed and its effectiveness has been verified through numerical analysis.

The results of the investigation conducted for buildings with different number of stories exposed to various earthquake records indicate that, in the case of elastic structures, the application of the SRSS and the Naderpour et al. [16] formulae allows impacts to be prevented by ensuring optimal minimum separation gap. Moreover, the use of the proposed equation to calculate the effective periods of inelastic buildings has been found to be the most effective one when the nonlinear behavior is concerned. It allows us to prevent earthquake-induced structural pounding by ensuring an adequate value of the seismic gap.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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