Adequacy of Required Separation Distance in AS1170.4-2007 to Avoid Seismic Pounding between Adjacent Buildings

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Abstract

Seismic poundings between inadequately separated building structures have been observed in all the previous major earthquakes, which usually caused local damage around the pounding areas, and in extreme cases, collapse of the building structures. AS1170.4-2007 requires the separation between adjacent buildings to be 1% of the building height to avoid seismic pounding. This paper presents intensive numerical simulations to examine the adequacy of this specification to preclude seismic pounding between RC frame structures under design earthquake loading defined for Perth. It is found that that AS1170.4-2007 may give inaccurate estimations of required separations and the estimated separations may be inadequate when considering structures founded on the site sub-soil classes De and Ee and with large differences in fundamental vibration frequencies. For any structures founded on the site sub-soil classes Ae, Be and Ce or any structures with small differences in fundamental vibration frequency, AS 1170.4-2007 provides a conservative approach for determining required separation distances to avoid pounding.

Keywords: Structural pounding, RC frame, required separation distance, frequency ratio, site conditions, seismic code

1. INTRODUCTION

Collisions between inadequately separated buildings have been observed in all the previous major earthquakes. Due to the differences in dynamic peculiarities of structures and seismic ground motion spatial variations, the adjacent buildings usually vibrate laterally out-of-phase and this inevitably leads to collisions if the separation distance between them is not adequate. Each time pounding occurs, building structures will sustain short duration large impact force not specifically considered in conventional designs. These impacts usually cause damages around the pounding areas of adjacent structures, and may amplify the overall dynamic responses of structures. Previous investigations revealed that pounding could damage non-structural members such as curtain walls, cause equipment shifting resulting in a loss of building functions, damage structural members and in extreme cases result in total collapse of buildings (Rosenblueth and Meli 1986, Kasai and Maison 1991, Hall 1994, Comartin et al. 1995, Uzarski and Arnold 2001, Jain et al. 2002, Kawashima et al. 2009, 2011, Chouw and Hao 2012). Figure 1 shows some pounding damages in 1999 Taiwan and 2011 Christchurch earthquake.

Fig. 1. Observed pounding damages between adjacent structures in Taiwan (a&b) and Christchurch (c&d)

The 1985 Mexico earthquake provides a stark demonstration of the seismic pounding hazards. Analysis of damage statistics indicated that pounding between adjacent buildings occurred in over 40% of the 330 collapsed or severely damaged buildings, and for at least 15% of them pounding was the primary cause of collapse (Roesenblueth and Meli 9186). More than 200 pounding cases were observed in the 500 buildings surveyed in San Francisco Bay Area after the 1989 Loma Prieta Earthquake (Kasai and Maison 1991). Old multi-storey masonry buildings, which had virtually a very small or no separation between each other, were mostly involved in serious pounding damages. Architectural damage was found in over 79% of them, while 21% of these buildings endured significant structural destruction. Similarly, wide spread pounding damage was observed, especially in the Christchurch CBD after the 2011 Christchurch earthquake (Chouw and Hao 2012). It was reported that pounding damage occurred in tall buildings as well as one and two storey low-rise buildings. Brittle unreinforced masonry (URM) buildings with large window or door openings are especially vulnerable to pounding; and spatial variation of ground movement due to excessive liquefaction of soil has a potential to increase the magnitude of relative response between adjacent structures and thus increase severity of damage.

Many seismic codes give recommendations on the minimum required separations between adjacent structures to preclude pounding. The method to determine the minimum required separation varies from code to code. For example the National Building Code of Canada (NBCC), Israeli Code and the Uniform Building Code recommend that the minimum separation is the sum of the maximum displacements of two adjacent buildings obtained by equivalent static analysis, while other codes specify a smaller value by using quadratic combination of the maximum displacement of two adjacent buildings (e.g., France), or taking a percentage of the simple sum of the maximum displacements. Other codes, such as the Chinese Seismic Design Code GBJ11-89 estimate the required minimum separation based on the seismic intensity and building height.

The Australian Standards earthquake design code, AS 1170.4-2007, states that pounding needs to be considered for structures over 15 m and in Earthquake Design Category II, or any structures of earthquake design category III. Clause 5.4.5 and 5.5.5 for Design Category II and III of AS 1170.4-2007 state that “This clause is deemed to be satisfied if the setback from a boundary is more than 1% of the structure height (Standards Australia, 2007). In other words, the required separation is equal to 1% of the adjacent buildings.

This paper evaluates the adequacy of this specification to avoid pounding of adjacent RC frame structures. Intensive numerical simulations are carried out. Adjacent RC frames of different vibration periods are considered. Both linear elastic and nonlinear inelastic analyses are carried out. Spatial ground motion time histories are simulated for the analysis. All the simulated ground motion time histories are compatible with the respective design spectrum defined in AS 1170.4-2007 for different site conditions in Perth. Ground motion spatial variations are modelled by an empirical coherency loss function (Hao et al. 1989). Influence of ground motion spatial variations on relative displacement response between adjacent buildings is also discussed.

2. STRUCTURAL MODEL

Two SDOF generic RC frame models as shown in Figure 2 are used to calculate the required separation distance to avoid pounding. Computer program DRAIN2D-X (Powell et al 1993) is used for the calculations. In order to introduce spatially varying ground motion inputs, instead of using a lumped mass supported by a column, a frame structure with a rigid floor supported by two columns are modelled. The span length of each structure is assumed to be 40 m.

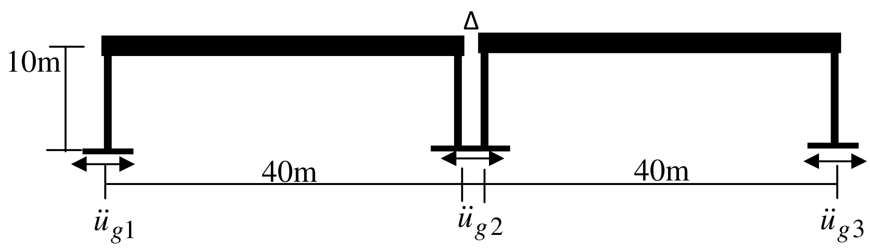


Fig. 2 Two generic SDOF RC frame models to calculate required separation distance

To model structural yielding and nonlinear response, a generic RC column is considered. The column has dimension of 500x500 mm, and reinforcement ratio 2.5% on each side. The reinforcement cover thickness is 100 mm. The concrete unconfined compressive strength is f'_c 32 MPa, tensile strength f'_{ct} 2 MPa, Young's modulus 30 GPa, yield strain 0.003; and the reinforcement steel yield strength f_{sy} 250 MPa and Young's modulus E_s 200 GPa. The parameters of the column yield surface are calculated as: $M_{y+}=M_{y-}=0.493\times10^6$ Nm, $P_{yc}=8.69\times10^6$N, $P_{yt}=2.88\times10^6$N, $M/M_y=1.7$, and $P/P_{yc}=0.34$. Figure 3 shows the column cross section, yield surface and the moment-rotation relation. A 15% strain hardening is assumed in this study. If only elastic response is interested, a very large yielding surface is used by specifying a very large value for yield moment and axial force in the calculations.

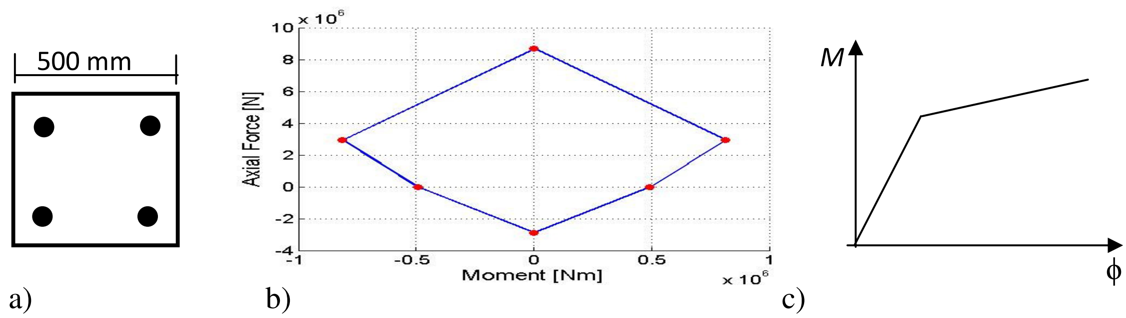


Fig. 3 Generic RC column: a) cross section, b) yield surface, c) Moment-rotation relation

Soil-structure interaction is not considered in the study. The relative displacement of the two building structures is calculated in numerical simulations. The largest relative displacement as defined in Eq.(1) is the required separation distance to avoid pounding.

$$\Delta = \max\left|y_1(t) - y_2(t)\right|_{T_D} \tag{1}$$

where $y_1(t)$ and $y_2(t)$ are the response time histories of two buildings, T_D is the duration of vibration.

Table 1. Parameters of frame models considered in the analysis

f_n(Hz)	ω_n(rad/s)	k (N/mm)	ξ	α (sec^{-1})	m (kg)
0.20	1.26	3762.50	0.05	0.13	2382.63
0.40	2.51	3762.50	0.05	0.25	595.66
0.60	3.77	3762.50	0.05	0.38	264.74
0.80	5.03	3762.50	0.05	0.50	148.91
1.00	6.28	3762.50	0.05	0.63	95.31
1.20	7.54	3762.50	0.05	0.75	66.18
1.40	8.80	3762.50	0.05	0.88	48.63
1.60	10.05	3762.50	0.05	1.01	37.23
1.80	11.31	3762.50	0.05	1.13	29.42
2.00	12.57	3762.50	0.05	1.26	23.83
2.20	13.82	3762.50	0.05	1.38	19.69
2.40	15.08	3762.50	0.05	1.51	16.55
2.60	16.34	3762.50	0.05	1.63	14.10
2.80	17.59	3762.50	0.05	1.76	12.16
3.00	18.85	3762.50	0.05	1.88	10.59
3.20	20.11	3762.50	0.05	2.01	9.31
3.40	21.36	3762.50	0.05	2.14	8.24
3.60	22.62	3762.50	0.05	2.26	7.35
3.80	23.88	3762.50	0.05	2.39	6.60
4.00	25.13	3762.50	0.05	2.51	5.96
4.20	26.39	3762.50	0.05	2.64	5.40
4.40	27.65	3762.50	0.05	2.76	4.92
4.60	28.90	3762.50	0.05	2.89	4.50
4.80	30.16	3762.50	0.05	3.02	4.14
5.00	31.42	3762.50	0.05	3.14	3.81

Relative displacement responses owing to out-of-phase vibrations generated by different vibration frequencies of two adjacent buildings are calculated. In the calculations, vibration frequency of frame 1 is fixed at f_1 = 1 Hz and remains unchanged. The vibration frequency of frame 2 varies from f_2 = 0.2 Hz to 5 Hz, with an increment of 0.2 Hz. For a SDOF system, the vibration frequency depends on the stiffness and mass. Without loss of generality, in this study, only mass of the frame 2 is changed to adjust the vibration frequency. The stiffness, which can be easily calculated for the portal frame shown in Figure 2 with the column dimensions and Young's modulus, remains unchanged in the simulations.

Since stiffness is fixed in the calculations, 5% mass proportional damping is considered. The damping coefficient is $C=\alpha M$ and $\alpha=2\xi\omega_n$, in which ξ is the damping ratio and ω_n is the circular natural vibration frequency. Table 1 lists the parameters defining the portal frame used in the analysis.

3. GROUND MOTION SIMULATIONS

Stochastic simulation of ground motion time histories as inputs in nonlinear time history analysis of structural responses is a common practice in earthquake engineering because at most engineering sites the strong motion record is not available. Moreover some researchers also believe that stochastically simulated ground motion time histories that are compatible to the design response spectrum are more proper input in structural response analysis than any strong motion record since a recorded strong motion time history is only a single realization of a random process that is very unlikely to occur again at the site under consideration. Many methods have been developed to simulate spatially varying response spectrum compatible ground motion time histories (Hao et al. 1989, Deodatis 1996, Bi and Hao 2012). In this study, the method developed by Hao et al (1989) is used to simulate ground motions at three structural supports. A total of 20 ground motion cases as listed in Table 2 are simulated. They represent spatial ground motions compatible to design response spectrum for different site conditions defined in AS 1170.4-2007 for Perth, and different levels of spatial variations modelled by an empirical coherency loss function (Hao et al. 1989),

$$\gamma_{ij} = \exp(-\beta d_{ij})\exp(-\alpha d_{ij}^{1/2} f^2)\exp(-i2\pi f \frac{d_{ij}}{c_a}) \tag{2}$$

where β is a constant, d_{ij} is the distance between the two locations i and j in the wave propagation direction, f is the frequency in Hz, and c_a is the apparent wave velocity which is assumed to be 1000 m/s in this study. α is a function in the following form

$$\alpha(f) = \frac{a}{f} + bf + c \quad f \le 10 \text{ Hz} \tag{3}$$

when $f > 10$ Hz, the α function is a constant and equals to the value at 10 Hz.

Three spatial variation conditions, representing highly, intermediately and weakly correlated ground motions are considered. The corresponding parameters are given in Table 3.

Most major codes require 2 to 4 independent ground motion simulations and calculations to get the average responses. In this study, to reduce the influences of uncertainties from ground motion phase angles on structural responses, 20 sets of simulations for each case are carried out by specifying a random phase angle. Average structural responses from 20 independent calculations are presented. In all the simulations, the ground motion duration is assumed to be 20.48 sec and the sampling frequency is set to be 100 Hz.

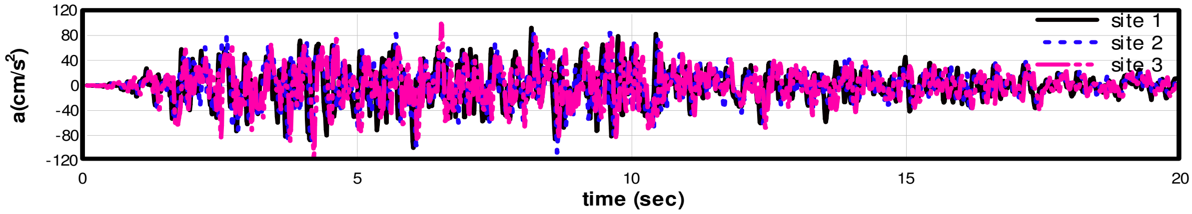
Table 2. Ground motion cases

Case	Soil type	Correlation
1	Rock (B_e)	Highly
2	Rock (B_e)	Intermediately
3	Rock (B_e)	Weakly
4	Rock (B_e)	Uniformly
5	Soft soil (D_e)	Highly
6	Soft soil (D_e)	Intermediately
7	Soft soil (D_e)	Weakly
8	Soft soil (D_e)	Uniformly
9	Strong rock (A_e)	Highly
10	Strong rock (A_e)	Intermediately
11	Strong rock (A_e)	Weakly
12	Strong rock (A_e)	Uniformly
13	Shallow soil (C_e)	Highly
14	Shallow soil (C_e)	Intermediately
15	Shallow soil (C_e)	Weakly
16	Shallow soil (C_e)	Uniformly
17	Very soft soil (E_e)	Highly
18	Very soft soil (E_e)	Intermediately
19	Very soft soil (E_e)	Weakly
20	Very soft soil (E_e)	Uniformly

Table 3. Parameters for coherency loss functions

Coherency loss	β	a	b	c
Highly	1.109×10^{-4}	3.583×10^{-3}	-1.811×10^{-5}	1.177×10^{-4}
Intermediately	3.697×10^{-4}	1.194×10^{-2}	-1.811×10^{-5}	1.177×10^{-4}
Weakly	1.109×10^{-3}	3.583×10^{-2}	-1.811×10^{-5}	1.177×10^{-4}

Figure 4 shows one set of simulated spatial ground motion acceleration and displacement time histories corresponding to ground motion case 1. Figure 5 shows the comparisons of response spectrum of typical simulated ground motions and the design response spectrum, and the comparison of coherency loss between simulated ground motion at two sites and the corresponding empirical coherency loss function. As shown, the simulated ground motion time histories match well the target design spectrum and empirical coherency loss function. These simulated time histories are used in the subsequent structural response analyses.



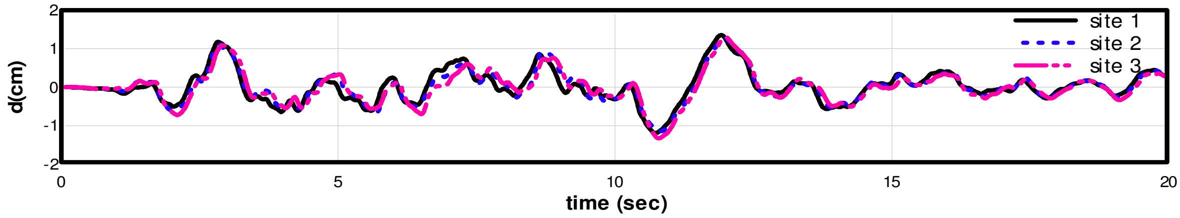


Fig. 4 Typical simulated ground motion acceleration and displacement at the three sites (Case 1)

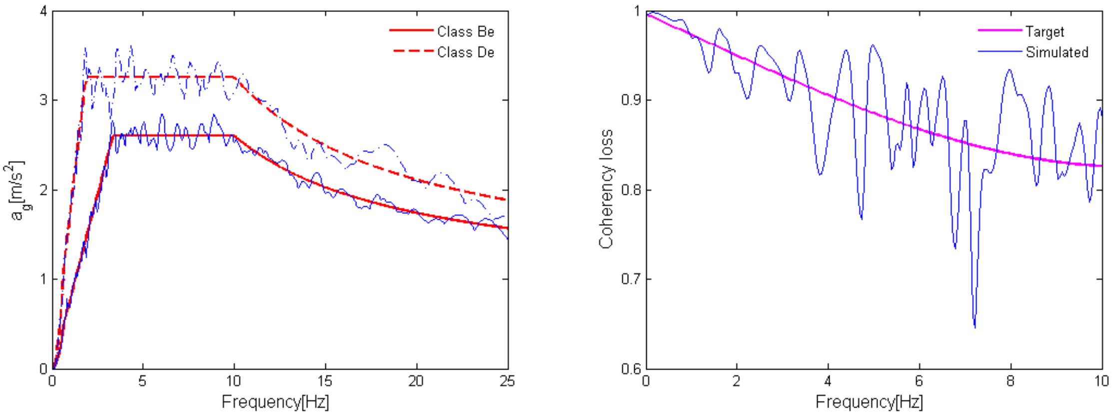


Fig. 5 Comparison of response spectrum and coherency loss of simulated spatial ground motions with the target design response spectrum and empirical coherency loss function

4. CODE DEFINED MINIMUM SEPARATION DISTANCE

The Australian Standards Earthquake Design Code, AS 1170.4-2007, requires that any building of earthquake design category II that is greater than 15 metres in height, or any building of earthquake design category III, must be separated from adjacent structures or set back from an adjacent building boundary to avoid pounding. The minimum set back distance stipulated by the code is 1% of the structure height (see clauses 5.4.5 and 5.5.5 of AS 1170.4-2007) (Standards Australia 2007).

To determine the separation distances required by AS 1170.4-2007 in the context of this study, the following equation given in the code is used to estimate the building vibration period

$$T_1 = 1.25 k_t h_n^{0.75} \tag{4}$$

where T_1 is the fundamental natural translational period of the structure, k_t depends on the structural type, it is 0.11 for moment-resisting steel frames and 0.075 for moment-resisting concrete frames; h_n is the height from the base of the structure to the uppermost seismic weight or mass, in metres. By re-arranging Equation (4) the relation between building height for a particular period can be found as

$$h_n = \left(\frac{T_1}{1.25 k_t}\right)^{\frac{1}{0.75}} \tag{5}$$

To model the majority of the building types in Perth a k_t value of 0.075 (for moment-resisting concrete frames) is chosen. By assuming that one frame exists on its building boundary, the required separation distance is calculated as the set-back distance required for the second frame.

By intuition, the flexible adjacent frame, which is taller, should be used to calculate the required separation distance. However, this is not stated in the code besides the statement that 'minimum set back distance of 1% of the structure height'. In practice the required separation distance may also be determined by the height of the adjacent short building as illustrated in Figure 6. The code does not specify which adjacent building should be used to calculate the required separation. Using the flexible (taller) adjacent building gives a conservative estimation. The calculated required separation distances between two buildings calculated by using 1% height of building 2 with increasing vibration frequency and decreasing height or by using the taller adjacent building are given in Figure 6 as a function of ratio of vibration frequencies, which will be compared with numerical simulation results to evaluate the adequacy of code specifications.

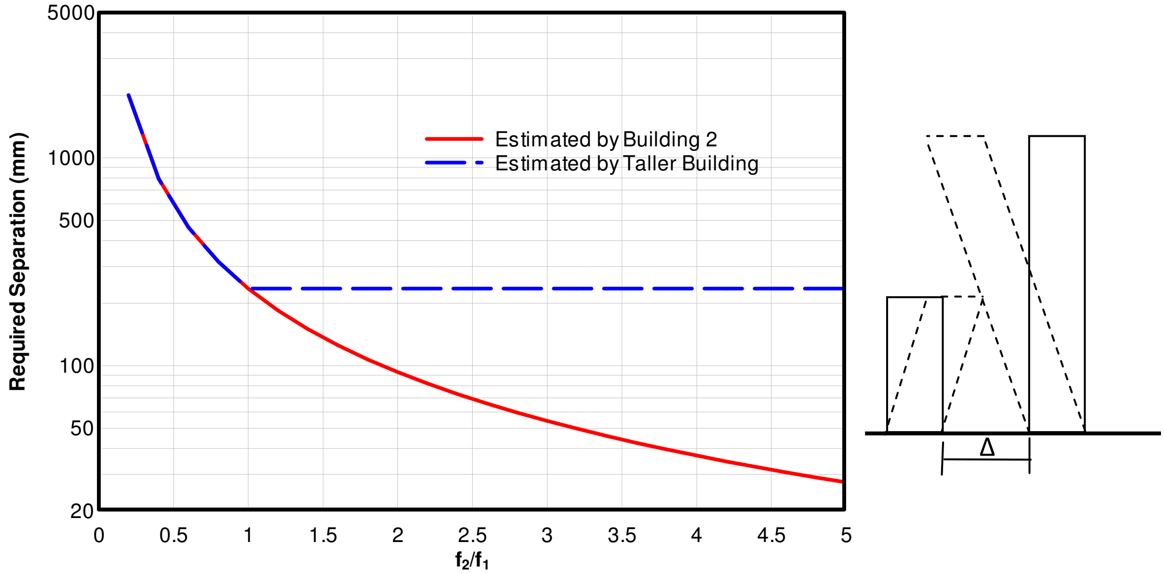


Fig. 6 AS 1170.4-2007 required separation distances

5. NUMERICAL RESULTS AND DISCUSSIONS

Numerical simulations are carried out to calculate relative displacement of two adjacent buildings with different vibration frequency ratios. For each case, 20 independent simulations are performed using 20 stochastically simulated spatial ground motion sets. Figure 7 shows the average relative displacement and the coefficient of variations of 20 simulations corresponding to ground excitation Case 5 and 17 obtained with linear and nonlinear time history analysis. As shown, the coefficients of variations are all substantially smaller than the corresponding mean values, indicating the mean values give unbiased estimations of required separations between two buildings to avoid pounding. Similar observations on responses from other ground motion cases can also be drawn. Therefore hereafter only mean values of 20 independent simulations are presented.

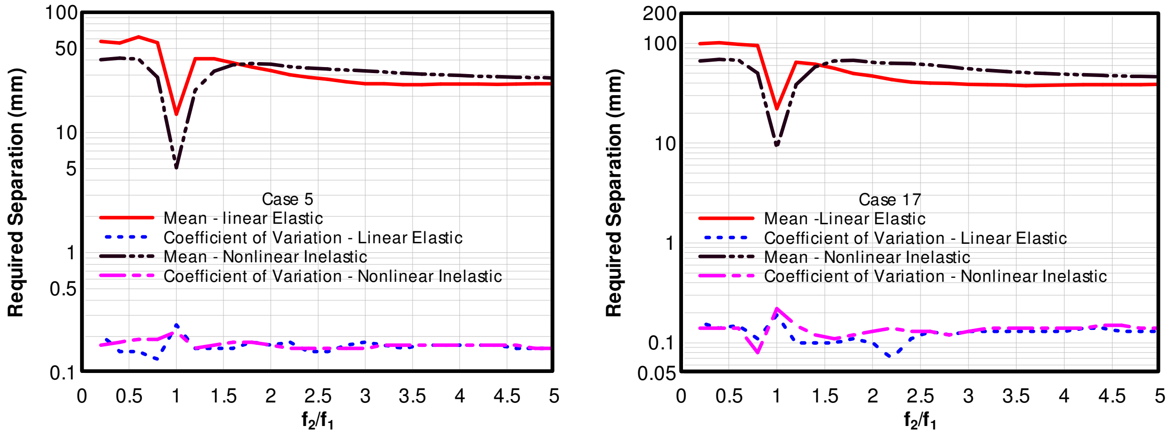


Fig. 7 Mean and coefficient of variation of the required separation distances between two buildings corresponding to ground motion cases 5 and 17 obtained from linear and nonlinear analyses

5.1 Linear and Nonlinear Response Analysis

As shown in Figure 7, linear and nonlinear response leads to quite different predictions of required separations. In general when the vibration frequency ratio is less than about 1.5, linear response analysis gives larger required separation distances than nonlinear analysis, while nonlinear analysis may result in a larger required separation distance when the vibration frequency ratio is larger than 1.5. The reason that nonlinear response results in smaller required separation is because yielding reduces structural stiffness, which in turn reduces the vibration frequency. Adjacent structures with low vibration frequencies tend to vibrate in phase. Therefore the required separation (relative displacement) is smaller although the actual displacement response of each building is larger than that obtained with linear elastic analysis.

When the vibration frequency ratio is large, implying the vibration frequency of the second building is large because that of the first building is fixed at 1.0 Hz. The displacement response of a very stiff second building is small, which leads to small relative response although highly out-of-phase vibration is expected. Yielding reduces structural stiffness and results in larger displacement responses, although the two buildings tend to vibrate more in phase, the relative displacement could be larger than that obtained from linear elastic analysis.

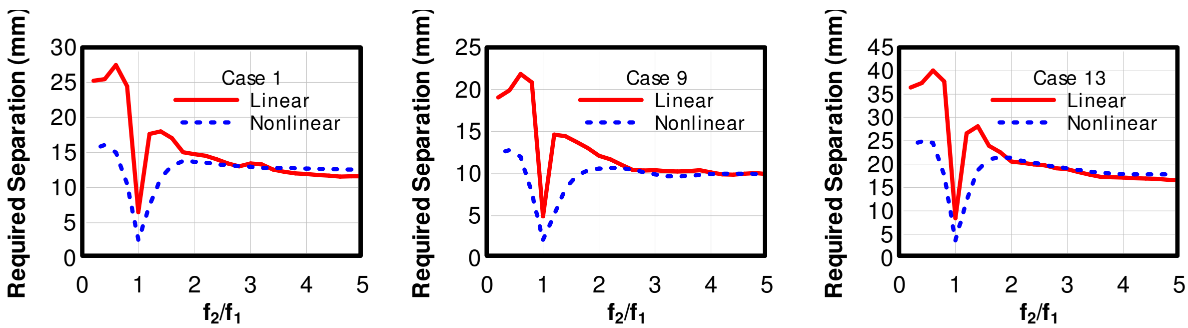


Fig. 8 Required mean separation distances obtained by linear and nonlinear analysis

The above observations are further confirmed by results shown in Figure 8 corresponding to different ground motion cases. In general neglecting nonlinear inelastic response in structural analysis may overestimate the required separation distances between two buildings to avoid pounding. In the following, only results from nonlinear inelastic responses are presented.

5.2 Influence of Ground Motion Spatial variations

Ground motion spatial variations induce relative displacement response between adjacent structures. When the vibration frequency ratio of two adjacent structures is 1.0, indicating the two structures will vibrate exactly in phase. The relative displacement response should be zero if the ground motion input is uniform. However, as shown in Figures 7 and 8, it is not zero at unit vibration frequency ratio because of spatially varying ground motions at the multiple supports of the structures. Figure 9 shows the relative displacement responses at different vibration frequency ratios obtained with different ground motion spatial variations. As shown ground motion spatial variation affects the required separations between adjacent buildings to avoid pounding. Its influence is most prominent when the two buildings have similar vibration frequencies. In the range of frequency ratio close to unity, neglecting ground motion spatial variation underestimates the required separations. When the two buildings have different vibration frequencies, however, the relative displacement response is induced primarily by out-of-phase vibrations of two buildings owing to different vibration frequencies. The influence of ground motion spatial variations is less prominent.

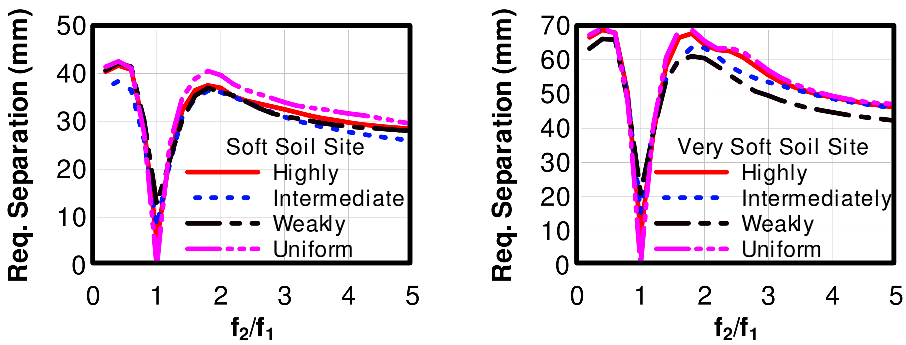


Fig. 9 Required separations obtained with different ground motion spatial variations

5.3 Required Separations for Structures on Different Sites

As shown in Figure 9, the required separation distances between buildings on very soft soil site is substantially larger than that of buildings on soft soil site. This is further observed in Figure 10, showing the required separation distances for buildings on sites of five different conditions defined in AS 1170.4-2007, obtained by assuming intermediately correlated spatial ground motions. As shown, the required separation distance increases when the site conditions becomes softer. This is expected because the total displacement response is larger when a structure sits on a soft site owing to larger ground displacement.

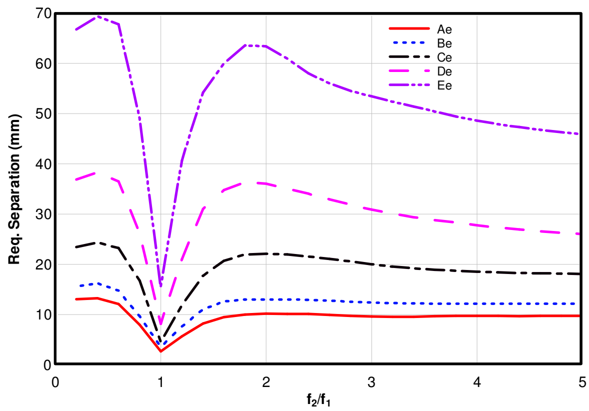


Fig. 10 Required separation distance for buildings on different sites

5.4 Comparison with Code Specifications

Figure 11 compares the code required separation distance between adjacent buildings to avoid pounding and the numerical simulation results for buildings on site of different conditions with intermediately correlated spatial ground motions. As shown, separation distance calculated by using 1% of the taller adjacent structure always overestimates the required separation distance to avoid pounding. However, if it is calculated as 1% of the second structure irrespective of its height as compared to the first structure, it may underestimate the required separation distance when two buildings locate on soft and very soft soil site with very different vibration frequencies. These results indicate that the code specifications may over- or underestimate the required separations between adjacent structures depending on the site and structural conditions, as well as the interpretation of the code definition. Overestimation results in a waste of land area and increases the construction cost, while underestimation may lead to pounding damage during earthquake ground shaking. Therefore, it is important to have reliable predictions of required separation distances between adjacent building structures.

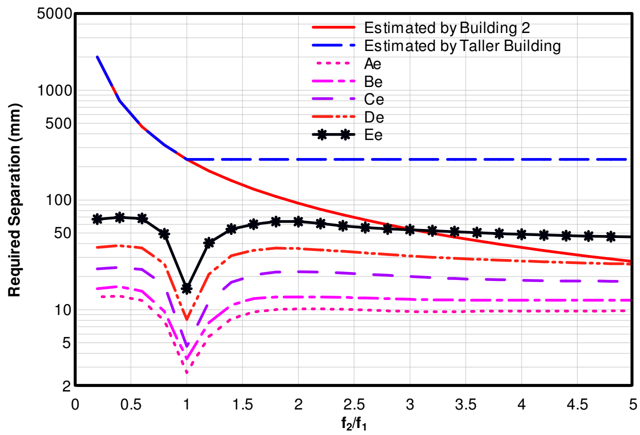


Fig. 11 Comparison of code specifications with the numerical simulation results

6. CONCLUSION

This paper presents numerical simulations of relative displacement response of adjacent building structures with different vibration frequencies and subjected to spatially varying ground motions.

Spatially varying ground motions are simulated as inputs in the analysis. The simulated ground motion time histories are compatible to design response spectra defined in Australian Earthquake Loading Code for various site conditions. Ground motion spatial variations are modelled by an empirical coherency loss function with highly, intermediately and weakly correlation assumption. Uniform ground motion input is also considered for comparison. Based on intensive numerical simulation results, it is found that relative displacement response between two building structures is generated primarily by ground motion spatial variations when the two buildings have similar vibration frequencies. When the two buildings have very different vibration frequencies, out-of-phase vibration of adjacent buildings owing to different vibration frequencies is the primary source for relative responses between two building structures. Neglecting nonlinear inelastic response usually overestimates relative response of two structures. Required separation distance defined in AS 1170.4-2007 may not give good estimations of the required separations between adjacent structures to avoid pounding.

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