Required Separation to Mitigate Pounding of Adjacent Building Blocks

Mohammed S. Masmoum
Civil Engineering Department
King Abdulaziz University
Jeddah, Saudi Arabia
ms.masmoum@gmail.com

Mohammed-Sohaib Alama
Civil Engineering Department
King Abdulaziz University
Jeddah, Saudi Arabia
sohaib.alama@hotmail.com

Abstract—**This research discusses the feasibility of using the required minimum separation distance based on SBC 301-2007. Moment resistance frames were designed with expansion joints requiring 400mm separation distance. Nonlinear response history analysis was conducted with four ground motions selected and scaled to match the risk-targeted response spectrum of NEOM city based on ASCE 7-16 provisions. An equivalent spring constant value based on floor lateral stiffness was selected as a gap link stiffness. Finally, an evaluation for the pounding response of adjacent blocks is presented along with the conclusions.**

Keywords-pounding; expansion joint; minimum seperation

I. INTRODUCTION

Saudi Arabian cities witness major development due to the high demand for residential housing and high-rise buildings. High-rise buildings require sophisticated designs since these flexible structures might include expansion joints that separate them from adjacent rigid structures. This scenario can be idealized by a high-rise tower surrounded by a podium or adjacent parking structure. The difference in mass and stiffness might make them move out-of-phase during strong ground motion events. This movement makes adjacent building blocks prone to pounding hazard. Saudi building code [1] requires a minimum separation distance to reduce or eliminate pounding hazard. The minimum separation distance is calculated based on the square root sum of squares (SRSS) of maximum inelastic drifts of adjacent building blocks. This article discusses the feasibility of using the required minimum separation distance by Saudi building code to guard against pounding hazards.

II. LITERATURE REVIEW

Over 40% of buildings were reported to be severely damaged or collapsed during the 1985 Mexico City earthquake. About 15% of these buildings collapsed due to pounding [2]. A survey following the 1989 Loma Prieta earthquake showed that more than 200 buildings were damaged due to pounding in a distance around 90km from the epicenter which indicates that pounding could be catastrophic for cities near or far from active faults. The survey concluded that a rational method is required to be enforced to mitigate the pounding hazard [3]. Many methods have been proposed to account for minimum required separation: 1) absolute sum of displacement (ABS), 2) square root sum of squares (SRSS), and 3) spectral difference method using double difference combination (DDC) rule [4-8]. SBC 301-2007 did adopt the concept of SRSS because of its simplicity, high accuracy and small differences in the minimum required separation distance comparing to DCC [9-10]. A comparison between these methods had been conducted with conclusion that SRSS can be practical and provide the required separation distance [11-12]. This article is discussing the feasibility of using the minimum separation distance required by SBC 301-2007.

III. METHODOLOGY

Neom city was selected as the study site. The building blocks are designed to satisfy code requirements for gravity and seismic loads. Also, those building blocks have different fundamental periods in order to increase the pounding likelihood. A 12-story building will be designed adjacent to 6-story building block. Variable separation distance values between the building blocks are assumed. A set of ground motions is selected and scaled based on ASCE 7-16 [13] §16.2.2&3 criteria. Nonlinear response history analysis was performed by SAP2000 [14]. Modeled building blocks are linked by gap link in order to measure the pounding force due to variable separation distances. Finally, a discussion for the results and research findings will be presented.

A. Building Design

SBC 301-2007 seismic uniform-risk probabilistic hazard maps indicate that Neom has a moderate risk of earthquake hazards comparing to other cities in Saudi Arabia. Values for short period (S_S=0.5sec) and 1 sec-period (S_1=0.13sec) accelerations have been selected. SBC 301-2007 §9.4.3 requires modifying these factors based on soil type. Due to absence of such information, soil class D had been assumed for conservatism. The modified accelerations (S_{MS}=0.70sec) and (S_{M1}=0.285sec) will produce a response spectrum defined as risk-targeted maximum considered earthquake (MCE_R) response spectrum. SBC 301-2007 §9.4.4 requires to divide S_{MS} and S_{M1} by 1.5 to produce design response spectrum accelerations (S_{DS}=0.446sec) and (S_{D1}=0.19sec). Also, it is assumed that the study location will include commercial buildings that have an occupancy important factor of type II (I_e=1). The suitable lateral force-resisting system for the study location based on the seismic design category (SDC=C) and (I_e=1) was intermediate reinforced concrete moment resisting frame. Structural system, response modification factor (R=4), over-strength factor (Ω_0=3), and deflection amplification factor (C_d=4.5) have been selected based on SBC 301-2007 Table 10.2 with Reliability factor (ρ=1) based on SBC301-2007 §10.3.3 requirements. Cast-in-place reinforced concrete frame with hollow-core slab system has been selected to resist all gravity loads. 12-story and 6-story building blocks with length of 18m and 3.6m story elevation were assumed. Figure 1 shows a plan for a high-rise tower and adjacent parking structure. The hatched area represents the effective slab width supported by the beam. The self-weight of the slab is equal to 53.6kN/m. The super-imposed dead load had been estimated to be 20.92kN/m. Live load had been assumed to be 19.2kN/m.

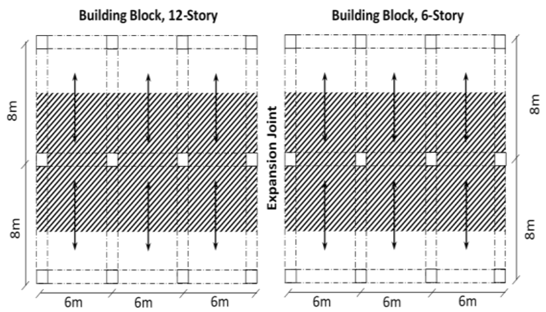

Fig. 1. Plan view for adjacent building blocks.

SBC 301-2007 §2.3.1 introduces basic load combinations. Based on SBC 301-2007 §2.3, for strength design approach, all structural elements must be designed using factored loads that are generated from different load combinations. The critical combination will govern the design of the member. The following combinations are required by the Saudi building code:

$$1.4D \tag{1}$$

$$1.2D+1.6L \tag{2}$$

$$1.2D+1.0E+0.5L \tag{3}$$

$$1.2933D+1.0Q_E+0.5L \tag{4}$$

$$0.9D+1.0E \tag{5}$$

$$0.8066D+1.0Q_E \tag{6}$$

Note that substitution for horizontal and vertical values for E in (3) and (5) had resulted in values of (4) and (6), where Q_E is defined as the horizontal lateral load due earthquake. Values of 35MPa and 45MPa concrete compressive strength were assumed for beams and columns respectively. The modulus of elasticity had been assumed as $4700\sqrt{f'c}$ based on SBC 304-2007 §8.5.1. The concrete will have a density of 2430kg/m^3 and thermal expansion coefficient of 9.9×10^{-6}. Takada hysteresis model was selected for concrete material. Stress-strain curve was defined based on unconfined Mander model with ultimate unconfined strain capacity of 0.005, strain at unconfined $f'c$ 0.002, and -0.1 for final compression slope. Grade 420MPa reinforcing steel rebars confirm ASTM A-615 [15] specification. The modulus of elasticity had been estimated as 200,000MPa. The steel rebars will have a density of 7850kg/m^3 and thermal expansion coefficient of 11.7×10^{-6}. Kinematic hysteresis model was selected for the steel rebars material. Simple stress-strain curve's defined based on ultimate strain capacity was 0.09, and the strain at onset of strain hardening was 0.01, and -0.1 for final compression slope. SBC 301-2007 §10.9 permits the use of equivalent lateral force to estimate the base shear with SDC C. The following equation estimates the base shear.

$$V = C_S W \tag{7}$$

where V is the estimated base shear ($V_{12story}$=455.73kN, V_{6Story}=437.52kN), W is the seismic effective weight depending on member self-weight and 100% of the dead load ($W_{12Story}$=19691.82kN, W_{6Story}=10169.61kN), and C_s is the seismic coefficient ($C_{s12Story}$=0.0232, $C_{s6story}$=0.0433).

SBC 301-2007 §10.9.3 requires that the fundamental period value from the computational model ($T_{12Story}$=2.885sec, T_{6Story}=1.082sec) should not exceed the product of approximate period and the upper limit variable. The upper limit approximate period values had been used to calculate base shear ($T_{a(upper)12Story}$=2.127sec, $T_{a(upper)6Story}$=1.140sec). SBC 304-2007 [16] §10.11.1 requires to reduce the moment of inertia during the elastic analysis to account for cracking of concrete. This approach is enforced if the bending moment at service level passes the cracking moment. The threshold values are 0.35Ig for beams and 0.70Ig for columns. Different reinforced concrete cross sections were defined in the computational model shown in Figure 2. Rigid zone had been defined for all column and beam joints with a value of 0.5. All cross sections satisfied the design requirements of SBC 304-2007 due to prescribed loading conditions. SBC 301-2007 §10.9.7.1 permits to use the fundamental period from the computational model in drift check calculations. The inelastic drift will be used to check inter-story drift limit. Inter-story drift should not exceed the product of 0.02 by story height as explained in SBC 301-2007 §10.12.1. SBC 301-2007 §10.12.2 requires a minimum separation distance between adjacent building blocks based on square root square sum of the maximum of maximum inelastic drift of the two adjacent building blocks at the same story level. The inelastic drift of the 6th floor from the 12-story and 6th roof from 6-story building block was used to determine the required separation distance ($\delta_{x12Story}$=198.9mm, $\delta_{x6Story}$=104.35mm). It is concluded that a separation of 224.61mm will be enough to reduce or eliminate the pounding hazard based on code provision.

B. Selection and Scaling of Ground Motion Records

ASCE 7-16 §16.2.2 requires the use of at least 11 ground motion records collected from the study site. Fewer ground motion records can be used when the study site ground motion intensity is considered low because of the expected low sensitivity of nonlinear model response [17]. In this study, four ground motion records were selected with respect to study site design spectrum curve as shown in Table I. There were no available records for the study site.

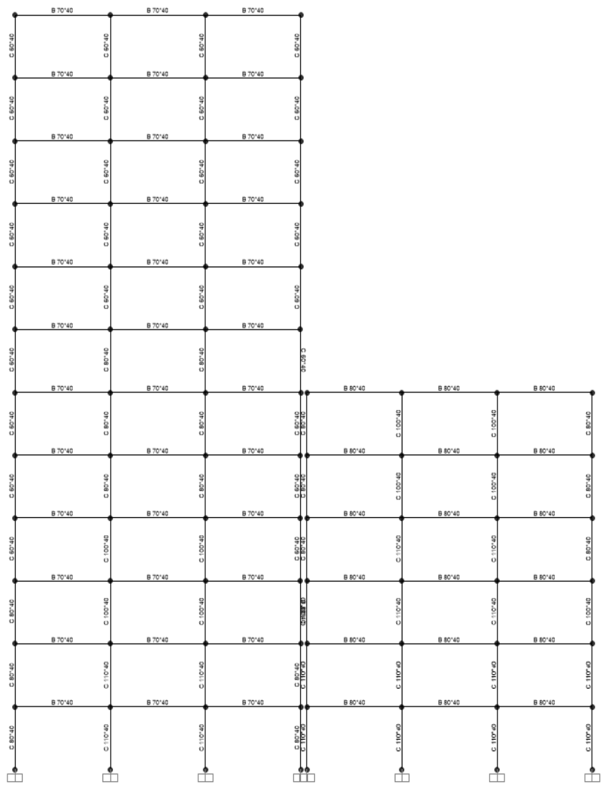

Fig. 2. Elevation view with cross sections detail.

ASCE 7-16 §16.2.2 permits to use records from another site with similar parameters in the absence of site ground motion records. Those parameters are Joyner-Boore distance (Rjb), fault control mechanism, and moment magnitude. Rjb distance is defined as the shortest distance from the study site to the surface projection of the fault. Rjb distance is measured from the projected area of Aqaba fault and is estimated between 15 to 45km. Slip-Strike faulting style is assumed for the Aqaba fault [18]. The intensity of the historical earthquakes in the study site is ranged from 4 to 6Mw. The record of maximum horizontal acceleration spectrum will be scaled to match risk-target response spectrum (2% probability of exceedance) and the average of records spectrum should not be less than 10% from the risk-target response spectrum curve within a range from 1.5 times structural fundamental period until 0.2 times the fundamental period as shown in Figure 3.

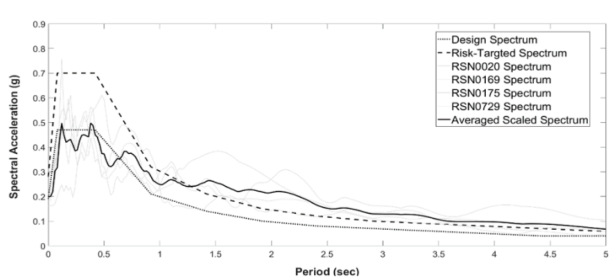

Fig. 3. Scaled ground motions.

C. Nonlinear Response Parameter Analysis

ASCE 7-16 11§16.3.2 requires using a 100% of the dead load as the initial condition for nonlinear response history analysis. Ramp function with duration of 30sec had been assumed for the initial condition load case. The proceeding nonlinear response history cases had been solved by implicit direct integration with Newmark-Beta method with values of γ=0.5 and β=0.25. The time step had been discretized with a value of 0.005sec, since all the ground motion records are discretized with similar value or more. The accuracy of the results has been verified by rerun of the analysis with half step size. It is found that both runs were stable, converged, and had similar pounding force [17]. ASCE 7-16 §16.3.5 requires a damping ratio that does not exceed 0.25 for building equivalent viscous damping. The value of 0.25 for damping had been selected for all the response history analysis load cases. Based on that, specified stiffness and mass proportional damping coefficients had been selected with 1st and 3rd period values from the flexible building blocks [19]. Geometric nonlinearity was not considered. For load case of nonlinear parameters, maximum and minimum time step was kept on default value. The maximum iteration for constant-stiffness and Newton-Raphson were taken as 10 and 40 per step respectively. The convergence tolerance had been selected with a value of 0.0001.

TABLE I. GROUND MOTION RECORD DETAILS

Record Serial Number*	RSN0020	RSN0169	RSN0175	RSN0729
Scale Factor	0.93	0.87	1.50	1.09
Earthquake Name	Northern Calif-03	Imperial Valley-06	Imperial Valley-06	Superstition Hills-02
Station	Ferndale City Hall	Delta	El Centro Array #12	Imperial Valley Wildlife Liquefaction Array
Year	1954	1979	1979	1987
Rjb distance (km)	26.72	22.03	17.94	23.85
Control Mechanism	Strike Slip	Strike Slip	Strike Slip	Strike Slip
Moment Magnitude	6.50	6.19	6.53	6.54

*Records were collected through University of California, Berkeley PEER Ground Motion Database (NGA-west2).

D. Gap Link Stiffness

Gap link is a numerical tool assigned to connect two joints located around the expansion joint which can be used to measure the pounding force intensity between the adjacent building blocks by defining a specific opening. If the total value of the displacement and opening exceed zero the link will not measure any pounding force since the building blocks are away from each other as shown in (8):

$$f = \begin{cases} (0)\, if\, (d + open) \geq 0 \\ K_{Gap}(d + open)\, if\, (d + open) < 0 \end{cases} \quad (8)$$

If the total value of the displacement and opening are less than zero, the link will measure the pounding force using linear elastic relationship as shown in (8). It is observed that there is a positive correlation between gap link stiffness and pounding force. The intent from using the link is to measure pounding force without any superfluous stiffness. The right stiffness value should assist finding a converged solution with reasonable pounding force. The nonlinearity of the pounding response analysis and its sensitivity to ground motion scaling intricate the process of finding the appropriate stiffness value. There are many proposals that relate axial stiffness of the connecting element to link stiffness. These relations are usually multiplied by the order of magnitude to reach a converged solution [7-12]. Authors suggest the use of in-series equivalent spring from lateral stiffness of the connected floors as shown in (9):

$$K_{Gap} = \frac{K_{12Story}\left(K_{6Story}\right)}{K_{12Story} + K_{6Story}} \qquad (9)$$

The floor lateral stiffness values in (10) and (11), can be quantified by restraining all the translation degree of freedom in the model for all the floors except the 6th floor of each building blocks. A dummy force equal to 100kN was assigned as a lateral force on the 6th floor of each building block. Building blocks have been analyzed separately to get the floor displacements ($D_{6th\text{-}Floor}$=0.0004m, $D_{6th\text{-}Roof}$=0.0008m). Note that that all columns have been modified with 0.7Ig ($K_{12Story}$=250,000 kN/m, K_{6Story}=125,000kN/m).

$$K_{12story} = \frac{F}{D_{6th-Floor}} \qquad (10)$$

$$K_{6Story} = \frac{F}{D_{6th-Roof}} \qquad (11)$$

From the previous relations, it is concluded that the equivalent spring stiffness is equal to 83,333kN/m. This value was used for response time history analysis.

IV. Results and discussion

Pounding forces were measured and summed from all assigned links. Various values of separation distance have been used to see the feasibility of the code required provision as shown in Figure 4. It was found that the SBC 301-2007 recommendation for approximately 400mm did successfully mitigate the pounding force for all the scaled records. Record RSN0175 required half of the code separation to eliminate pounding force. It was noticed that record RSN0169 was recorded from the same event but it required a full separation distance to mitigate to pounding force. A potential reason for RSN0175 result is the low frequency content comparing to RSN0169 and difference in recording station location. Furthermore, it was observed that separation distance smaller than 50mm results in high pounding intensity. This gives an indication that adjacent building blocks do not support each other in the case of small separation distances since the force intensity amplified. A potential reason behind this amplification is the difference in fundamental periods between the adjacent building blocks.

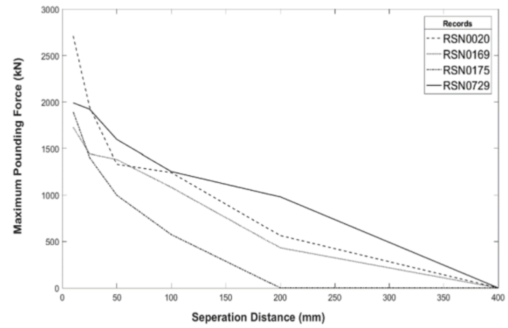

Fig. 4. Maximum pounding force as function of seperation distance.

It was also observed that the pounding force of record RSN0020 was not reduced by increasing the separation distance from 50mm to 100mm. A similar characteristic can be noticed for record RSN0729 from 100mm and 200mm. This shows the importance of providing a full SBC 301-2007 code separation distance to mitigate pounding force. It also contradicts the finding of the record RSN0175 which require half of the recommended distance. All records exhibit a unique pounding response due to increase in the separation distance. The pounding force of RSN0175 reduces rapidly with the separation distance, unlike RSN0020 and RSN0169 records which had a moderate reduction. Noticeably, RSN0729 pounding reduction was affected slowly by the increase of the separation distance. It can be seen that this record had been taken from a site with liquefied soil. This result shows that pounding response could not easily be mitigated in soil site Class F [20] based on soil classification of SBC 301-2007 §14.1.1 or ASCE 7-16 §20.3.1.

V. Conclusion

On the basis of the results obtained during the course of this work and the assumptions made, the following conclusions were found:

- The code that required separation provision did successfully mitigate the pounding hazard based on study assumptions.
- It is important to adopt the exact separation distance since nonlinear response history analysis revealed that pounding force exists in separation distance less than the required value.
- Nonlinear response history analysis can be used routinely to evaluate the pounding hazard for new designed structures.
- Equivalent spring stiffness based on floor lateral displacement can be assumed as gap link stiffness to give a converged solution. If the integration still does not converge, the stiffness value might need a further multiplicand to reach a converged solution.
- It is important to conduct a nonlinear response history analysis for sites that are characterized with liquefied soil.

Since pounding response could not be mitigated easily by applying the code separation provision.

- It is encouraged to seek more reliable methods to mitigate pounding hazard other that separation. For example, it was required to have 400mm to fully mitigate the pounding hazard based on the study assumption. A lot of technical effort and financial resources are required to cover this separation distance.

REFERENCES

[1] SBC Committee 301, Structural - Loading and Forces. Saudi Building Code National Committee, 2007

[2] E. Rosenblueth, R. Meli, "The 19875 earthquake: causes and effects in Mexico City", Concrete International, Vol. 8, pp. 23-34, 1986

[3] K. Kasai, B. F. Maison, "Building the 1989 pounding damage during Loma Prieta earthquake", Engineering Structures, Vol. 19, No. 3, pp. 195-207, 1997

[4] V. Jeng, K. Kasai, B. F. Maison, "A Spectral Difference Method to Estimate Building Separations to Avoid Pounding", Earthquake Spectra, Vol. 8, No. 2, pp. 201-223, 1992

[5] J. Penzien, "Evaluation of building separation distance required to prevent pounding during strong earthquakes", Earthquake Engineering & Structural Dynamics, Vol. 26, No. 8, pp. 849-858, 1997

[6] J. H. Lin, "Separation distance to avoid sesmic pounding of adjacent buildings", Earthquake Engineering and Structural Dynamics, Vol. 26, No. 3, pp. 395-403, 1997

[7] R. E. Valles, A. M. Reinhorn, Evaluation, Prevention and Mitigation of Pounding Effects in Building Structures, National Center for Earthquake Engineering Research, State University of New York at Buffalo, 1997

[8] H. P. Hong, S. S. Wang, P. Hong, "Critical building separation distance in reducing pounding risk under earthquake excitation", Structural Safety, Vol. 25, No. 3, pp. 287-303, 2003

[9] D. Lopez-Garcia, T. T. Soong, "Evaluation of current criteria in predicting the separation necessary to prevent seismic pounding between nonlinear hysteretic structural systems", Engineering Structures, Vol. 31, No. 5, pp. 1217-1229, 2009

[10] R. Jankowski, S. Mahmoud, Earthquake-Induced Structural Pounding, Springer International Publishing, 2015

[11] M. J. Favvata, "Minimum required separation gap for adjacent RC frames with potential inter-story seismic pounding", Engineering Structures, Vol. 152, pp. 643-659, 2017

[12] M. Isteita, K. Porter, "Safe Distance Between Adjacent Buildings To Avoid Pounding in Earthquakes", 16th World Conference on Earthquake Engineering, Santiago, Chile, January 9-13, 2017

[13] ASCE/SEI Standard 7-10, Minimum Design Loads for Buildings and Other Structures, American Society of Civil Engineers, Reston, VA, USA 2010

[14] Computers and Structures Inc, CSI Analysis Reference Manual, Computers and Structures Inc., Berkeley, California, USA, 2016

[15] ASTM A615/A615M-18e1, Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement, ASTM International, 2018

[16] SBC Committee 304, Structural - Concrete structures, Saudi Building Code National Committee, 2007

[17] Applied Technology Council, Guidelines for nonlinear structural analysis and design of buildings. Part I - general, National Institute of Standards and Technology, U.S. Department of Commerce, 2017

[18] H. S. Saffarini, "Ground motion characteristics of the November 1995 Aqaba earthquake", Engineering Structures, Vol. 22, pp. 343-351, 2000

[19] D. R. Pant, A. C. Wijeyewickrema, "Structural performance of a base-isolated reinforced concrete building subjected to seismic pounding", Earthquake Engineering & Structural Dynamics, Vol. 41, No. 12, pp. 1709-1716, 2012

[20] S. Naserkhaki, M. El-Rich, F. N. A. A. Aziz, H. Pourmohammad, "Separation gap, a critical factor in earthquake induced pounding between adjacent buildings", Asian Journal of Civil Engineering, Vol. 14, No. 6, pp. 881-898, 2013