Simplified model for earthquakes pounding analysis of buildings

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International seismic codes, give some requirements for building separations, as a result of sever damage due to pounding. The Codes ignore the in-phase vibration between adjacent buildings, which are subjected to the same earthquake excitation. The requirements of codes for building separation are examined in this research. A close insight to the behavior of adjacent Multi Degree of Freedom systems (MDF) is highlighted. A model of two adjacent Single Degree Of Freedom systems (SDF) is used to conduct this study. The systems have a fundamental time period ranging from 0.1 to 1.0 seconds with step equal to 0.1 seconds. They have five different height ratios (0.1, 0.25, 0.50, 0.75, & 1.0) of the main height. The nonlinear time step dynamic analysis was used to determine the required separation between each building pair *"S_{AB}"* to avoid pounding under different design levels of earthquakes. The estimated distances S_{AB} between SDF systems versus the corresponding ratios of their fundamental time periods were plotted. The curve was used to estimate the required separations between MDF systems by using the correlation between few selected modes of vibrations of both buildings.

تضع الكودات العالمية بعض القيود والمتطلبات لتحديد المسافات التى يجب تركها بين المبانى المتجاورة لمنع حدوث تدمير لها نتيجة تخبطها ببعضها بفعل الزلازل . بصفة عامة فأن الكودات العالمية تهمل الاهتزازات الحادثة بين المبانى المتجاورة فى المستوى الواحد عندما تتعرض للهزات الارضية . وقد تم فى هذا البحث اختبار قيود ومتطلبات الكودات العالمية لتحديد المسافات بين المبانى لمنع حدوث التخبيط كذلك تم تسليط الاضواء على كيفية التنبأ بتصرف المبانى المتجاورة ذات درجات الحرية المتعددة . وقد قدم فى هذا البحث نموذج لمبنيين متجاوريين كل منهما ذات درجة الحرية الواحدة وقد اختبر هذا النموذج لمجموعة من المبانى ذات هزات ذاتيه تتراوح بين ١ر من الثانية الى ثانية كاملة (كل ١ر من الثانية) ولارتفاعات تتراوح بين (١ر ، ٢٥ر ، ٥ر ، ٧٥ر ، ١) كنسبة من أرتفاع المبنى الرئيسى . وقد تم استخدام التحليل الديناميكى اللاخطى لتحديد المسافات المطلوبه بين المبانى المجاورة لمنع حدوث التخبيط لقوى زلزالية مختلفة الشدة تتراوح من متوسطة الى شديدة . وفى هذا البحث تم عمل منحنى يمثل العلاقة بين المسافات المطلوبة بين المبانى لمنع حدوث التخبيط والنسبة بين الهزات الذاتية للمبانى المتجاورة بالنسبة الى بعضها البعض. وقد وظفت هذه العلاقة للتنبؤ بالمسافات المطلوبة بين المبانى ذات درجات الحرية المتعددة لمنع حدوث التخبيط .

Keywords: Pounding analysis, Spectral analysis, Earthquake Engineering

1. Introduction

Structural pounding refers to the lateral collisions between buildings during earthquakes. It occurs when adjacent buildings vibrate out of phase and when the separation distance is not sufficient to allow them to vibrate freely. Each time a collision occurs, the buildings are subjected to impact forces, which are not accounted for in the design process and can amplify the dynamic response of the buildings. That is, neglecting the effects of pounding leads to non-conservative building design because the story drifts, shear and overturning moments in the stories above the pounding level will be underestimated.

As a result of sever seismic events in the last twenty years, the interest of pounding has become important due to large amount of structural damage such as what had happened in Mexico city 1985 and Loma Prieta 1988 [1,2].

In order to account for these forces, some seismic codes, Uniform Building Code (UBC-1988) and National Building Code of Canada (NBCC-1990) give some requirements for building separations as follows.

UBC code requires the minimum separation between adjacent buildings to be at least equal to the value obtained by the absolute sum rule as:

$$S_{AB} = [U_A + U_B]. \qquad (1)$$

S_{AB} is the Separation distance required to preclude pounding U_A & U_B is the peak lateral displacements at the possible pounding location under the no parading condition in buildings A & B.

The NBCC code requires the minimum separation between buildings be equal to:

$$S_{AB} = R\,[U_A + U_B]. \qquad (2)$$

R is the force reduction factor.

It is obvious that both of the codes ignored the in-phase vibration of the two adjacent buildings that are already subjected to the same earthquake excitation. Therefore, most recent researches indicate the need for more studies to examine and recheck the code requirements. This is because the codes require separations, are large and unacceptable from the technical view, i.e. the difficulty in using the expansion joints [1,3,4].

This paper uses the time history dynamic analysis, PC-ANSR program ref. [5], to perform that kind of analysis. Models of two adjacent Sigle Gegree of Freedon (SDF) systems that have different fundamental time periods and/or different height ratios, were used to conduct this study. The model is used to determine the required separation to avoid pounding between adjacent multi degree of freedom buildings. In the following brief descriptions of ground motion records, methods of analysis will be presented.

2. Ground motion records

Ten ground motions records were used in this study. Their peak accelerations are within the range of 0.179g to 0.4898g. The characteristics of the chosen ground motions are presented in table 1.

3. Structural models and assumptions

Ten single degree of freedom systems of reinforced concrete water towers are used to conduct this study. Their fundamental time periods range from 0.1 to 1.0 second with step equal to 0.1 second. They were designed to carry the dead load and live load according to Egyptian code of 1993. In this study, the building, which has fundamental time period equal to 1.0 second, is chosen as the main building. Then, the other buildings were put adjacent to it, to form the required building pairs to conduct this study. The layout of the water tower, member properties, and the fundamental time period are presented in fig. 1 and table 2, respectively.

In order to study the effect of heights' variations on the minimum required separation "S_{AB}" between adjacent buildings, when both buildings have similar and/or different fundamental time period. The bm7d'mgs of 0.4 and 0.8 second fundamental time period were redesigned with different height ratios (.0.10, 0.25, 0.50, 0.75, & 1.0) of their main height. Table 3 contains the member properties, masses and time period for each height ratio for the building of 0.8-second time period.

Two dimensional computer models were developed for pair of adjacent buildings. It was based on gross section and nominal material properties. The model incorporates lumped masses at the floor level. Fig. 2 shows the basic two-dimensional model which is used for each pair buildings.

4. Methods of analysis

Two methods of analysis were used during this study, the static analysis (Double Difference Combination rule, (DDC), and the time history dynamic analysis (PC-ANSR program).

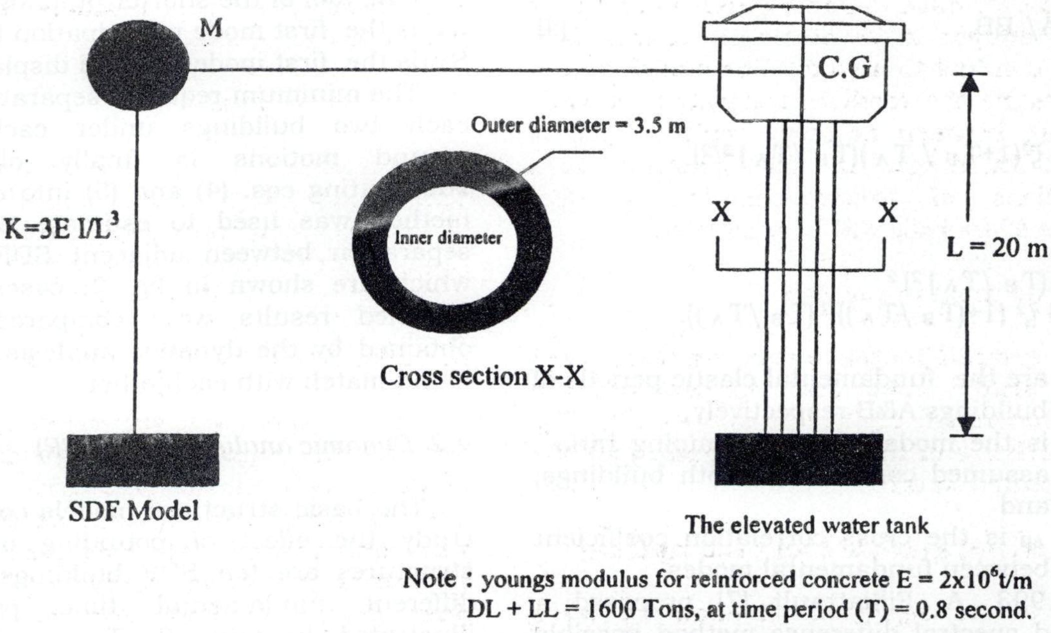
5. Static analysis (DDC)

This method was suggested by [1,6,7] to estimate the maximum relative displacement between two linear multiple degrees of freedom systems. It is based on the response spectrum method, [8]. This method has an advantage over other methods (The Absolute Sum Rule, The Root Squares of Sum of Squares) because it accounts for the

Table 1
Characteristics of earthquake ground motions

Earthquake records	Date of earthquake	Peek accel. (%) of g)	Ground vel. (in/sec)	Ground displ. (in)	Duration time (sec)
Elcentro- ELC -S 00 E	5/8/1940	0.348	13.15	4.88	55.76
Taft -TAF – S609	7/21/1952	0.179	6.97	4.13	55.76
Olympia OLY-S 86 W	4/29/1965	0.198	5.12	1.65	83.62
Old Bridge Oldb-N 21 E	2/9/1971	0.315	6.73	2.01	62.92
South Olive Soll- S 53 E	2/9/1971	0.241	8.58	5.71	56.8
South Olive Sol2- S 37 E	2/9/1971	0.196	7.28	5.71	57.96
Cholame Shandon Par-N 6515	6/27/1966	0.489	30.71	10.31	45.66
Park field Par3- N 85 E	6/27/66	0.434	10.00	2.72	45.10
Loner California Loc-N90 W	12/30/1934	0.182	4.53	2.44	89.96
Hollywood HWDN90E	2/9/1971	0.211	8.31	5.79	81

Note : The cross sectional area "A", moment of inertia "T" and the stiffness "K" equal ($6.28m^2$, $12.565m^4$ and 9423.75 ton/m`) respectively .



Note : youngs modulus for reinforced concrete $E = 2x10^6 t/m$
DL + LL = 1600 Tons, at time period (T) = 0.8 second.
M = weights (DL+LL)/ Gravity acceleration "g" .

Fig. 1. The general layout for the SDF building.

Table 2
Members properties for the used SDF system

Building No.	1	2	3	4	5	6	7	8	9	10
Masses (M)= Weight/g (ton.sec^2 /m)	239	193.4	152.8	117	85.94	59.68	38.19	21.98	9.55	2.39
Fundamental time period(T), (sec)	1.0	0.9	0.8	0.7	0.6	0.5	0.4	0.3	0.2	0.1

Jeng [6], estimated the minimum building separation to prevent seismic pounding based on the difference of the relative motions between two particular points in the adjacent buildings, where pounding is expected. They simplified the problem by using the fundamental mode only as an approximation for the multi degree of freedom response of both buildings. Finally, the minimum required separation S_{AB} is given by:

$$S_{AB} = SQR.[\, U_A^2 + U_B^2 - 2\, \xi_{AB}\, U_A\, U_B]. \qquad (3)$$

Where U_A&U_B are the maximum displacements of buildings A & B, respectively, which are obtained from the first mode spectral analysis.

$$\zeta_{AB} = AA/\ BB, \qquad (4)$$

where;

$$AA = [\ 8\ \zeta^2(1+T_B\ /\ T_A)(T_B\ /T_A\ )^{3/2}],$$

and

$$BB = [1-(T_B\ /T_A\ )^2]^2 + [4\ \zeta^2\ (1+(T_B\ /T_A\ ))^2\, (T_B\ /T_A\ )].$$

T_A & T_B are the fundamental elastic periods of buildings A&B respectively,

ζ is the modal viscous damping ratio , assumed common for both buildings, and

ζ_{AB} is the cross correlation coefficient between fundamental modes.

In 1993, A. Filliatrault [7] proposed a simplified spectral difference method possible inclusion in future cede editions. In his procedure, the fundamental m shape is obtained approximately by using the Canadian code static analysis procedure, for regular buildings. The static lateral deflections of each buildings was calculated under the inverse triangular distribution of design seismic loads. Then, the obtained lateral floor displacements are normalized to obtain the approximate fundamental mode of vibration.

The maximum displacement for each adjacent building under each design level excitation, at the floor level where pounding is expected is given by:

$$U_{MAX} = A_{P1} * \alpha_1 * S_{D1}. \qquad (5)$$

Where;

A_{P1} is the first mode components at the level where pounding is expected (usually at the roof of the shorter buildings),

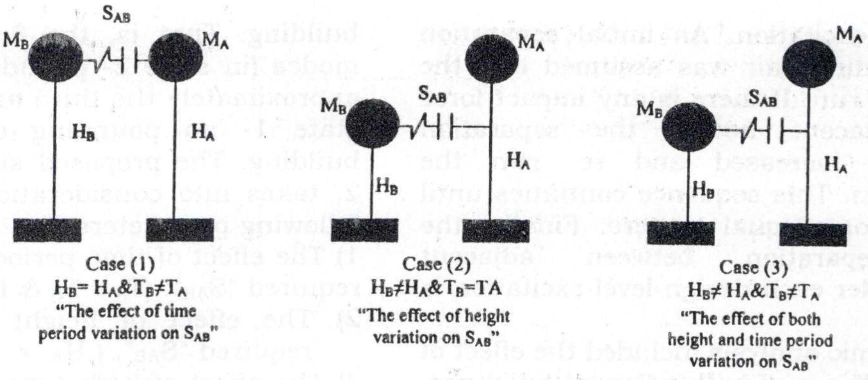
α_1 is the first mode participation factor, and

S_{D1} is the first mode spectral displacement.

The minimum required separation between each two buildings under each designed ground motions is finally obtained by substituting eqs. (4) and (5) into eq. (3). This method was used to estimate the required separation between adjacent SDF buildings, which are shown in fig. 2, cases 2&3. The obtained results were compared to those obtained by the dynamic analysis. They were found match with each other.

4.2. Dynamic analysis (PC-ANSR)

The basic structural models considered to study the effect of pounding on adjacent structures are ten SDF buildings that have different fundamental time periods, as illustrated in table 2. Two - dimensional computer models as shown in fig. 2, for each SDF building pair was developed. It is based



Case (1) $H_B= H_A \& T_B \neq T_A$ "The effect of time period variation on S_{AB}"

Case (2) $H_B \neq H_A \& T_B = TA$ "The effect of height variation on S_{AB}"

Case (3) $H_B \neq H_A \& T_B \neq T_A$ "The effect of both height and time period variation on S_{AB}"

Fig. 2. The two dimensional structural model.

Table 3
Members properties at different height ratios when the fundamental time period equal to 0.8 second

Height ratio H_B/H_A	Area , A(m²)	Inertia, A (m²)	Stiffness, K (ton/m)	Mass, M (ton.sec²/m)	Time period $T=2\pi/\sqrt{K/M}$
0.1	0.126	0.0013	975	15.30	0.7867
0.25	1.57	0.05	2400	38.22	0.7925
0.5	3.14	0.785	4710	76.45	0.80
0.75	4.71	3.976	7068.44	114.678	0.7999
1.00	6.28	12.566	9424.5	152.90	0.79989

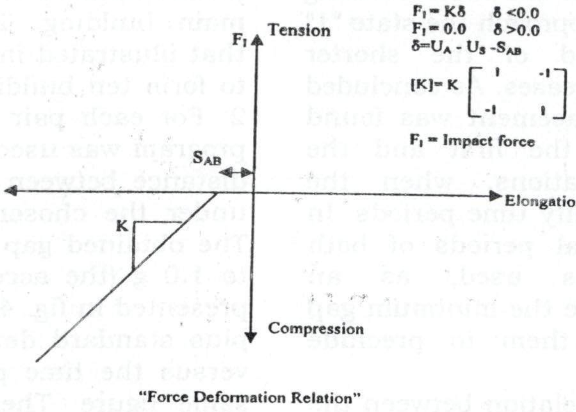


Fig. 3. Nonlinear elastic axial gap element.

on gross sections, nominal material properties and lumped masses at the floor level.

In this study, the pounding effect through a non-linear elastic axial gap element is considered. It was used to introduce a linear compressive spring between adjacent nodes where pounding is expected as shown in fig. 3. Each pair is subjected to the ten ground motions. The dynamic analysis is performed through the nonlinear time step method. It should be noted that the Newton-Raphson iteration with stiffness reformation every one time step, a time step equal to 0.01 second and Rayleigh damping based on 5% critical damping in the fundamental modes of vibration for both adjacent buildings were specified during this study. A time step dynamic analysis program (ANSR-1, PC-ANSR) [5], is the tool to perform that.

The program was used in determining the required separation to avoid pounding between each adjacent building under each design level excitation. An initial separation between building pair was assumed and the program was run. If there is any impact force between adjacent nodes, the separation distances is increased and re- run the program again. This sequence continues until the impact force equal to zero. Finally, the required separation between adjacent buildings under each design level excitation is obtained

The dynamic analysis included the effect of mass and stiffness of both adjacent buildings. The analysis does not include the energy dissipation resulting from building damage at the pounding locations as well as, the soil-structure interaction.

5. The proposed model concepts

In past researches, [2,9], the pounding analysis between adjacent buildings was idealized as having two states of vibrations. In state "1" (no pounding case), both buildings vibrate by themselves. In state "2" (pounding case), both buildings vibrate in contact. The fundamental time period of the taller building was found progressively approach the state "1" fundamental time period of the shorter building, as the mass increases. As concluded in [8], the spectral displacement was found mainly generated from the first and the second modes of vibrations, when the building has close proximity time periods. In ref [10], the fundamental periods of both adjacent buildings was used, as an approximation, to estimate the minimum gap distance "S_{AB}" between them to preclude pounding.

In this study, the correlation between the first two modes of vibration of adjacent buildings will be used to estimate the gap distance "S_{AB}", when they have close proximity fundamental time periods. But, when they have widely spaced fundamental periods, the correlation between the first two modes of the shorter building and the first four modes of the taller buildings will be used to estimate the " S_{AB} ". This may be explained as follows.

During contact period, the fundamental period of taller building will approach the state "1" fundamental period of the shorter building. That is, the first and the second modes (in state 2- pounding case) will equal approximately the third and fourth modes (in state 1- no pounding case) of the taller building. The proposed simplified model, fig. 2, takes into consideration the effect of the following parameters.

1) The effect of time periods variations on the required "S_{AB}". ($T_A \neq T_B$ & $H_A = H_B$)
2) The effect of height variations on the required "S_{AB}". ($H_A \neq H_B$ & $T_A = T_B$)
3) The effect of both time periods and height variations on the required "S_{AB}".

For studying the effect of these parameters on the required "S_{AB}", three cases of adjacent SDF buildings, as shown in fig. 2, were used to conduct this study. The obtained results were compared to both UBC-code and DDC-rule results.

5.1. *The effect of time periods variations on the required "S_{AB}", ($T_A \neq T_B$ & $H_A - H_B$)*

To recommend the minimum gap distance "S_{AB}", the building with fundamental time period equal to 1.0 second was chosen as the main building. Then, the other buildings, that illustrated in table 2, were put beside it to form ten buildings pairs, as shown in fig. 2. For each pair of buildings, the PC-ANSR program was used to obtain the required gap distance between them to prevent pounding under the chosen ground motions records. The obtained gap distances were normalized to 1.0 g (the acceleration gravity). They are presented in fig. 4. Their mean and the mean plus standard deviation values were plotted versus the time period ratios TB/TA in the same figure. They were also illustrated in table 4. From fig. 4, the minimum separation increases gradually till the fundamental time periods ratio T_B/T_A is up to 0.8. It also reduces sharply to zero, when T_B/T_A ratio is between 0.8 and 1.0.

5.2. *The effect of height variations on the required "S_{AB}". ($H_A \neq H_B$ & $T_A = T_B$)*

To study the effect of height variation on the minimum gap distance "S_{AB} ", the building with fundamental time period equal to 0.8

Table 4
The mean and the mean plus standard deviation for the minimum gap distance between adjacent SDF Systems, normalized to 1.0g, damping=5%"

T_B/T_A	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1.00
Mean	8.26	8.46	8.92	9.23	9.96	10.57	10.31	10.12	7.24	0.00
M+St.de.	11.29	11.4	11.87	11.49	12.06	14.57	13.69	13.91	9.96	0.00

second was chosen as the main building. Then, the other buildings, which have the same time period with different height ratio, that illustrated in table 3, were put beside it to form five buildings pairs, as shown in fig. 2, case 2. For each pair of buildings, the PC-ANSR program was used to obtain the required gap distance between them to prevent pounding under two ground motions records, (EL Centro,1940 and Taft, 1952), that illustrated in table 1. The obtained results are presented in fig. 5, as well as the obtained results by both the DDC rile and UBC-88 code. It was found that, the minimum separation " S_{AB} " decreases as the height ratio H_B/H_A increases for the results obtained by both time history analysis and DDC-rule, as shown in fig. 5.

According to DDC rule, eq. (3), if both building have the same time period of vibration, the correlation coefficient "ζ_{AB}" eq. (4) , will equal to 1.0 and the required "SAB" will equal to the difference between the spectral displacement of both buildings (S_{AB}= U_A-U_B). If additionally the buildings have the same height, the "S_{AB}" will equal to zero. According to UBC-88 code, eq. (1), the correlation between modes of vibrations is not considered.

5.3. The effect of both time periods and height variations on the required "S_{AB}"

To study the effect of both height ratio and time period ratio variations on the minimum gap distance "S_{AB}", the buildings with fundamental time period equal to 1.0 second was chosen as the main building. Then, the buildings, which have 0.8 and 0.4 second fundamental time period with different height ratios, that illustrated in table 3 for the building with 0.8 second for example, were put beside it to form five buildings pairs for each time periods ratio, as shown in fig. 2, case 3. For each pair of buildings, the PC-ANSR program was used to obtain the required gap distance between them to prevent pounding under two ground motions records, (El Centro, 1940 for T_B/T_A =0.8 and Taft 1952 for T_B/T_A =0.4), that illustrated in table 1. The obtained results are presented in fig. 6, as well as the obtained results by both the DDC rule and the UBC-code. It was found that, the minimum separation "SAB" increases as the height ratio HB/HA increases for all methods, as shown in fig 6. It was also recognized that, the results of DDC-rule are in close proximity to the time history analysis results.

According to DDC rule, eq. (3), if both buildings have widely spaced time period of vibration, the correlation coefficient"ζ_{AB} ", eq. (4), has a minimum value and the required "S_{AB}" will equal approximately to the square root of sum of squares of the spectral displacement of both buildings .i.e., S_{AB} = $(U_A{}^2+U_B{}^2)^{½}$. If additionally the buildings have the same height, the "S_{AB}" will be maximum.

It is recognized that, the gap distance has a maximum value, when the adjacent buildings have the same height and- different fundamental time periods. Thus, the obtained values for S_{AB} in fig. 4 are the maximum gap distance between adjacent buildings. Therefore, they

Five steel moment resisting frame buildings, (have two, four, six, seven and eight stories), were used, in ref. [11], to recommend need to be corrected according to the height ratio H_B/H_A of adjacent buildings.

6. The correction factor

From studying the effect of both time periods and height variations on the required "S_{AB}", it was found that the maximum "S_{AB}" occurs, when the adjacent buildings have the same height (H_B/H_A=1.0) and different time

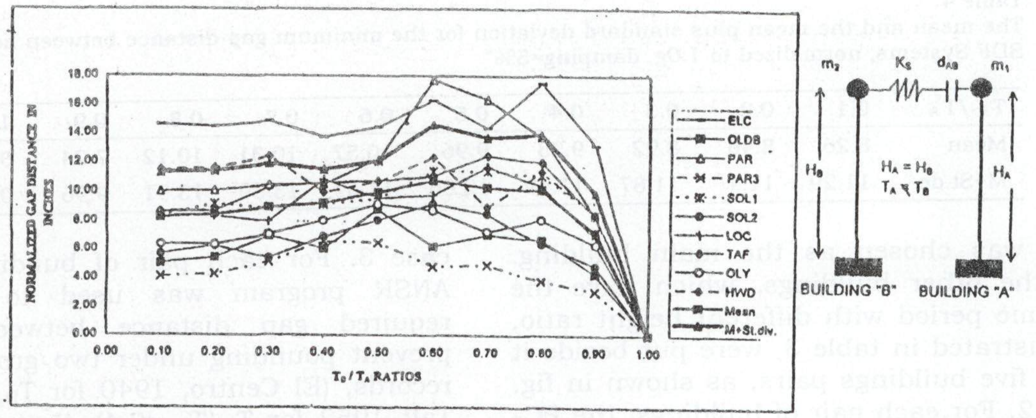


Fig. 4. The mintmum gap distance between adjacent SDF systems, normalized to 1.0 g, damping = 5%.

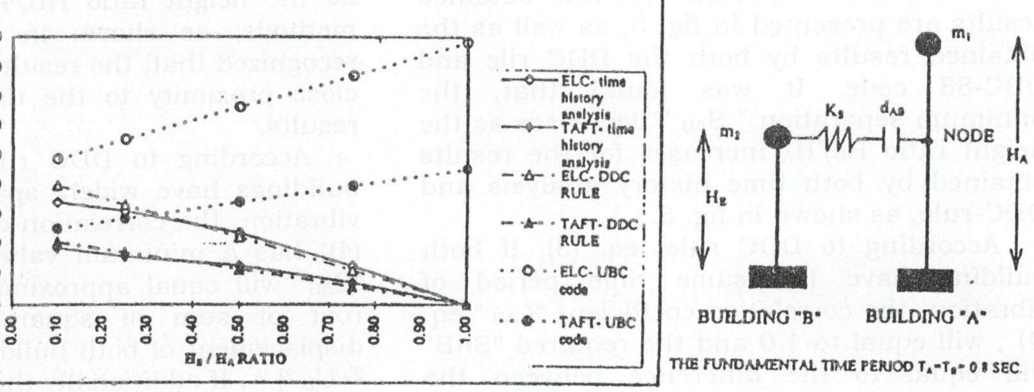


Fig. 5. The effect of height ratios variation on the GAP distance between adjacent SDF systems of similar fundamental time periods, TA=Ts = 0.8 Second, damping = 5%.

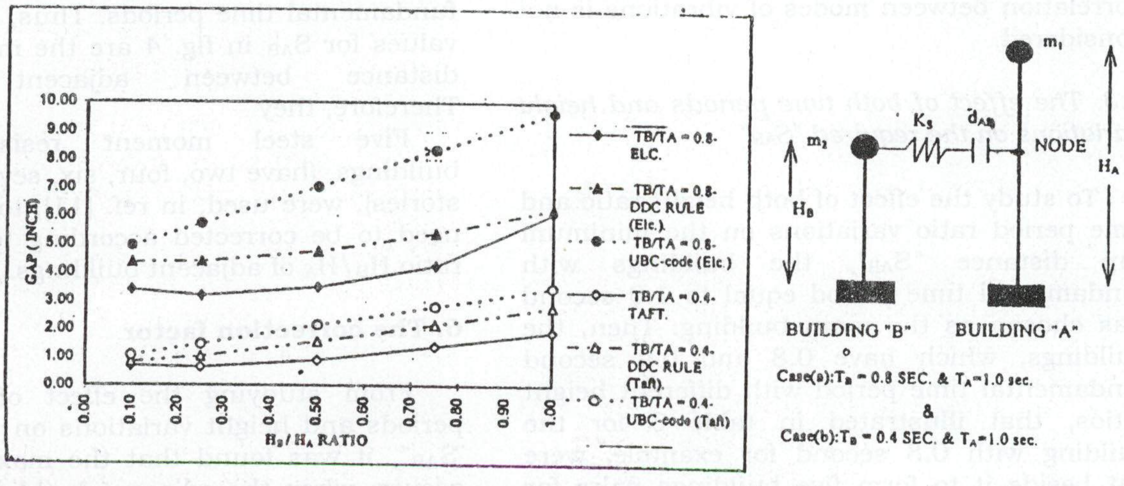


Fig. 6. The Effect of height ratios variations on the requred GAP distance between adjacent SDF systems of different fundamental tims periods, damping = 5%.

periods. The obtained results, in fig. 6, by both PC-ANSR and the DDC rule were found match with each other approximately. Therefore, the DDC rule was used to obtain the required correction factor. The computation procedure will be explained in the following.

Data

T_A= 1.0 sec., T_B = 0.8 sec., H_B/H_A = 0.75

Solution

Use the response spectral method to determine the maximum relative displacement, assuming 5% of the critical damping and maximum ground acceleration equal to 0.348g, ref. [10]. Hence, UA (H_B/H_A=1.0) = 5.22 inches, U_A (H_B/H_A=3/4) = 3.915 inches and UB=4.42 inches.

From eq. (4):

ζ_{AB} =0.1656.

From eq. (3):

S_{AB} (H_B/H_A=1.0) = 6.2564 inches,
S_{AB}(H_B/H_A=3/4) = 5.3974 inches.

The required correction factor equal to:

S_{AB}(H_B/H_A=3/4) / S_{AB} (H_B/H_A=1.0) = 5.3974/6.2664 = 0.8627.

The correction factor is illustrated in table 5, for most cases of different time periods and height ratios. In the following, the obtained relations between the height ratio and time periods ratio, fig. 4, will be used with the correction factor to estimate the minimum gap distance between adjacent MDF buildings.

Application

Five steel moment resisting frame buildings, (have two, four, six, seven and eight stories), were used in ref. [11], to recommend the minimum separation between adjacent MDF buildings. The gap distance, which was obtained from ref. [11], were plotted in fig. 7 and table 6. In the present study, the proposed model is applied on the same pairs of buildings. The method procedure will be explained in the following example.

Table 5
the suggested correction factor, based on DDC rule eq. (3)

H_B/H_A	0.10	0.25	0.50	0.75	1.00
T_B/T_A					
0.1	0.10	0.25	0.50	0.75	1.00
0.2	0.12	0.26	0.50	0.75	1.00
0.3	0.23	0.32	0.53	0.76	1.00
0.4	0.30	0.37	0.555	0.77	1.00
0.5	0.40	0.455	0.6	0.79	1.00
0.6	0.54	0.57	0.675	0.825	1.00
0.7	0.57	0.60	0.69	0.83	1.00
0.8	0.7	0.7	0.76	0.86	1.00
0.9	0.9	0.875	0.836	0.89	1.00

Table 6
The mean and the mean plus standard deviation of the required separation between buildings to avoid pounding, normalized to 1.0g , based on dynamic analysis, damping= 5% , ref.[14]

T_B/T_A	0.25	0.50	0.75	0.88	1.00
Mean	12.93	15.36	20.28	14.77	0.00
Mean plus std.Dev.	17.25	18.86	27.28	20.01	0.00

Example

There are two cases of adjacent buildings: (a) Closely spaced fundamental time periods (TB/TA >0.80). (b) Widely spaced fundamental time periods (TB/TA < 0.80). In the following a numerical solution will be given for each case.

Case (a): Seven stories building beside eight stories buildings

The calculated first and second time periods for both buildings are:

TB1 = 0.68 sec. TA1 = 0 77 sec.
TB2 = 0.23 sec. TA2 = 0.26 sec.

The correlation between the modes of vibrations gives the following time periods ratios:

TB1/TA1 = 0.88 TB2/TA2 = 0.88
TB2/TA1 = 0.30 TA2/TB1 = 0.38

From table 4 or fig. 4, the mean values and the mean plus standard deviation values, which are corresponding to TB/TA ratios (HB=HA), are obtained. From table 5, The correction factor, which are corresponding to TB/TA ratios, are obtained. Table 7 contains the corresponding obtained values versus the time period ratios. By multiplying the obtained values to the correction factor. Then, using the Square Root of Sum of Squares to obtain the suggested values for gap distance between adjacent MDF buildings.

SAB(Mean) =[(7.36) 2 *2+(7.85) 2 +(8.10) 2] ½ =15.384 inches
SAB(Mean+S.D.) =[(10.12) 2 *2+(10.45) 2+(10.22) 2] ½ =20.456 inches.

Table 7
The corresponding mean values, the mean: plus standard deviation values and the correction factors versus the time periods ratios

T_B/T_A	0.88	0.88	0.30	0.38
Mean values	7.816	7.816	8.92	9.168
Mean plus Std. Deviation values	10.75	10.75	11.87	11.566
The correction factor	0.942	0.942	0.88	0.884

Case (b): Two stories building beside eight stories buildings

The calculated first and second time periods for shorter building and the first four time periods for taller building are:

TB1 = 0.24 sec. TA1 = 0.77 sec.
TB2 = 0.09 sec. TA2 = 0.26 sec.
TA3 = 0.16 sec. T_{A4} = 0.12 sec.

The correlation between the modes of vibrations gives the following time periods ratios.

$T_{B1}/T_{A1} = 0.31$ $T_{B1}/T_{A2} = 0.92$
$T_{B2}/T_{A1} = 0.12$ $T_{B2}/T_{A2} = 0.35$
$T_{A2}/T_{B1} = 0.67$ $T_{B2}/T_{A3} = 0.56$
$T_{A4}/T_{B1} = 0.50$, $T_{B2}/T_{A4} = 0.75$.

From table 4 or fig. 4, the mean values and the mean plus standard deviation values, which are corresponding to T_B/T_A ratios ($H_B=H_A$), are obtained, as above. From table 5, the correction factor, which are corresponding to T_A/T_B ratios. are obtained, as above. By multiplying the obtained values to the correction factor. Then, using the Square Root of Sum of Squares to obtain the suggested values for gap distance between adjacent MDF buildings.

$S_{AB(Mean)}=[(2.90)^2+(2.09)^2+(3.13)^2+(5.21)^2+(5.46)^2+(6.17)^2+(6.64)^2+(4.53)^2]^{1/2}=13.50$
$S_{AB(Mean+S.D.)}=[(3.84)^2+(2.85)^2+(4.03)^2+(7.17)^2+(7.11)^2+(8.25)^2+(8.97)^2+(5.48)^2]^{1/2}=17.88$

Finally, the obtained results, for each pair of buildings, by the proposed model and dynamic analysis, is presented in table 8. As shown in table 8, the obtained results by the suggested model are generally 5 to 10 percent above the time history analysis results.

7. Conclusions

Models of two adjacent SDF systems, which have different fundamental time period and/ or different height ratios, were used to conduct this study. The model is used to determine the required separation to avoid pounding between adjacent multi degree of freedom buildings. This research examines and rechecks the requirements of codes for building separation and gives a close insight

Table 8
The comparison between the proposed method and time history dynamic analysis for adjacent MDF buildings

Values case of adjacent buildings	Mean values			Mean+standard deviation			Notes
	Proposed method	Dynamic analysis, ref.[14]	Proposed/ dynamic %	Proposed method	Dynamic analysis, ref.[14]	Proposed/D ynamic %	
2-8	15.50	12.93	1.04	17.88	17.25	1.04	*
4-8	17.10	15.36	1.11	22.85	18.86	1.21	*
6-8	21.92	20.27	1.08	29.569	27.27	1.084	*
7-8	15.35	14.766	1.04	20.46	20.00	1.02	**

*The correlation is between the 1st and2nd modes of the shorter buildings and the first four modes of the taller buildings, (TB/TA <0.80).

**The correlation is between the 1st an 2nd modes of both buildings,(TB/TA >0.80) .

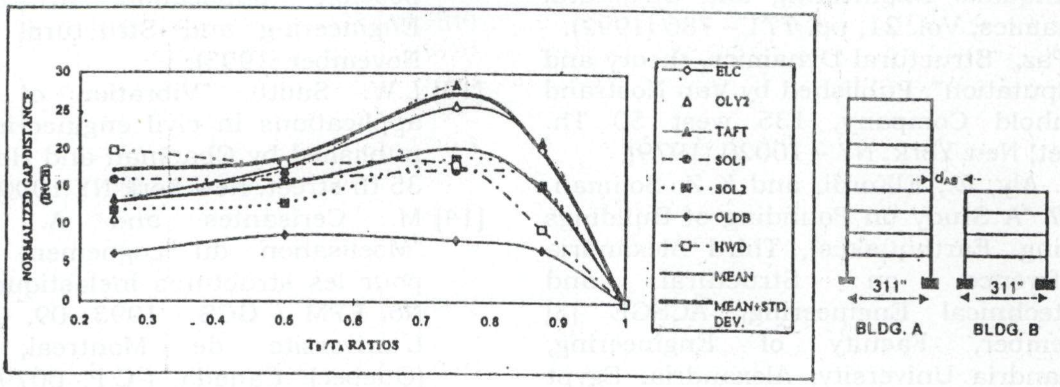


Fig. 7. Minimum separation between buildings to avoid punding pounding, normalized to 1.0 g, based on dynamic analysis, damping=5%, ref. [14].

to the behavior of adjacent Multi Degree of Freedom (MDF) systems. It was found that the UBC-88 code requirements give overestimated values than those predicted by both the time history analysis and the DDC-rule.

The nonlinear time step dynamic analysis was used to determine the required separation between each building-pair "SAB" to avoid pounding under different design levels of Earthquakes. The estimated distances SAB between SDF systems versus the corresponding ratios of their fundamental time periods were plotted and figs. (4,5 and 6). These curves were used to estimate the required separation between Multi Degree of Freedom systems by using the correlation between few selected modes of vibrations of both systems.

The obtained results by the proposed model and dynamic analysis, as shown in table 8, are generally 5 to 10 percent above the time history analysis results. In one case, it is 21% above the time history analysis results. Finally, it was recommended to use the proposed model in the future Egyptian code editions for estimating the minimum gap distance between adjacent buildings to preclude pounding.

References

[1] A. Filiatrault, and M. Cervantes, "Pounding of buildings during earthquakes, a Canadian perspective, ", Can. J. Civ. Eng., Vol. 21, pp. 251-265 (1994).

[2] B.F.Maison, and K.Kasai, "Analysis for type of structural pounding", J.Struct. Eng. ASCE 116, pp. 957-977 (1990).

[3] A. Filiatrault, B--Folz and H.G.L,Prion, "seismic analysis of structurally interconnected steel frames", Sixth Canadian conference, Earthquake Engineering, Toronto (1991).

[4] K. Kasai, B.F.Maison, V.Jeng, and D.J.Patel, "A study on earthquake pounding between adjacent structures", Sixth Canadian Conference, Earthquake Engineering, Toronto (1991)

[5] B.F. Maison, " PC - ANSR : A Computer Program for Nonlinear Structural Analysis", National Information Service for Earthquake Engineering, University of California, Berkley, CA (1992).

[6] V.Jeng, K. Kasai, and A Jagiasi "The separation to avoid -seismic pounding ", Earthquake Engineering, Tenth World Conference 1992, Ballgame, Rotterdam, ISBN 905410 0605 (1992)

[7] A. Filiatrault, and M.Cervantes, "Separation between buildings to avoid pounding during earthquakes", presented for possible publication in the Canadian Journal of Civil Engineering, Oct. (1993).

[8] A.D. Kiureghegian, "A Response spectrum method for random vibration" EERC report, UBC / EERC - 80-15, Earthquake Engineering Research Center, Univ. of California, Berkley, CA. 94720 (1980).

[9] B.F. Maison and K.Kasai, "Dynamics of pounding when two buildings collide",

Earthquake Engineering and Structural Dynamics, Vol. 21, pp. 771 - 786 (1992).

[10] M. Paz, "Structural Dynamics, theory and computation", Published by Van Nostrand Reinhold Company, 135 west 50 Th. street, New York, NY - 10020 (1979).

[11] A S. Aly, E., ElKordi, and K Z. Soliman, 1997 "A Study on Pounding of Buildings During. Earthquakes", Third Alexandria Conference on Structural and Geotechnical Engineering, ACSGE [3] December, Faculty of Engineering, Alexandria University, Alexandria, Egypt (1997)

[12] A. Filiatrault, and Sheldon Chery, "Analytical prediction of experimental building pounding", presented for possible publication in Earthquake Engineering and Structural Dynamics, November (1993).

[13] L.W. Smith, "Vibration of structures applications in civil engineering design", published by Cbapman and Hall, 25 west 35 th street, New York NY 10001 (1988).

[14] M. Cerisantes and A. Fdiatrault, "Moelisation du cognement seismique pour les structures inelastiques", Report No. EPM / GCS - 1993 -09, Campus de L'universite de Montreal, Montreal (Quebec), Canada, (-C.P. 6079, SUCC.A, H3 C) (1993).

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