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Frequency Domain Analysis for Geometric Nonlinear Seismic Response of Tall Reinforced Concrete Buildings

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ABSTRACT

This paper aims to study the second-order geometric nonlinearity effects of P-Delta on the dynamic response of tall reinforced concrete buildings due to a wide range of earthquake ground motion forces, including minor earthquake up to moderate and strong earthquakes. The frequency domain dynamic analysis procedure was used for response assessment. Reinforced concrete building models with different heights up to 50 stories were analyzed. The finite element software ETABS (version 16.0.3) was used to analyze reinforced concrete building models.

The study reveals that the percentage increase in buildings' sway and drift due to P-Delta effects are nearly constant for specific building height irrespective of the seismic design category assigned to the building. Generally, increase in building lateral displacement and story drift due to P-Delta effects for all seismic design categories is less than 2% for 10 story buildings, whereas this increase for 20 stories or taller buildings is significant with a maximum value around 16% for 50 story building. As for column forces, the study shows that, generally, columns bending moment increases and shear force decreases when P-Delta effects accounted for. In conclusion, the study recommended that the effects of P-Delta need to be addressed for all SDCs allowed by ASCE7-10 and the most important factor to abandonment P-Delta effects is the building height limit.

Keywords: equivalent lateral force procedure, P-Delta effect, high rise buildings, response spectrum analysis, reinforced concrete.

تحليل مجال التردد للاستجابة الزلزالية غير الخطية للمباني الخرسانية المسلحة المرتفعة

الخلاصة

تهدف هذه المقالة لدراسة تاثير السلوك الاخطي للازاحات من الدرجة الثانية ل بي-دلتا (P-Δ) على الاستجابة الحركية للمباني الخرسانية المسلحة المرتفعة بسبب شدة مختلفة لقوى الحركة الأرضية الزلزالية بما في ذلك زلزال بسيط يصل إلى زلزال معتدل اوقوي. تم استخدام اسلوب التحليل الحركي لمجال التردد لتقييم الاستجابة الزلزالية. تم تحليل نماذج مختلفة من المباني الخرسانية المسلحة وبارتفاعات مختلفة تصل الى خمسين طابقا. تم استخدام برنامج العناصر المحددة ETABS (الإصدار16.0.3) لاجراء تحليل الاستجابة الزلزالية لنماذج الابنية الخرسانية المسلحة .

كشفت الدراسة أن نسبة الزيادة المئوية في الازاحة الجانبية للمباني وانحرافها بسبب تأثيرات (P-Δ) هي نفسها تقريباً بالنسبة لارتفاع مبنى محدد بغض النظر عن فئة التصميم الزلزالي المخصصة للمبنى. وبشكل عام ، فإن الزيادة في الازاحات الجانبية وانحراف الطوابق للابنية نتيجة لتأثيرات بي-دلتا لجميع فئات التصميم الزلزالي هي أقل من 2٪ للمباني ذات 10 طوابق ، في حين أن هذه الزيادة للمباني ذات 20 طابقا او اعلى هامة مع قيمة قصوى بحدود 16% للمباني ذات الخمسين طابقا. أما بالنسبة للقوى في الاعمدة ، فقد أوضحت الدراسة أنه عموماً عزم الانحناء في الاعمدة يزداد وقوة القص تتناقص عندما يؤخذ بالاعتبار

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تأثير بي-دلتا. في الختام، أوصت الدراسة بأن تؤخذ تأثيرات بي-دلتا في الاعتبار لجميع فئات التصميم الزلزالي التي تسمح بها المواصفة الامريكية ASCE7-10 وان العامل الاهم لإهمال تاثير بي-دلتا (P-Δ) هو حد ارتفاع المبنى.

الكلمات الرئيسية: طريقة القوى الجانبية المكافئة, تاثير بي-دلتا, الابنية المرتفعة, تحليل طيف الاستجابة, الخرسانة المسلحة.

1. INTRODUCTION

To determine design forces resulting from loads acting on a building there are, generally, three types of analysis that can be carried out, as follows, **Powell, 2010**:

- The first type is small displacements analysis, in this type, equilibrium is considered in the undeformed position, and the compatibility relationships are assumed to be linear. In this case, geometric nonlinearity is neglected.
- The second type is large displacements analysis. In this type, equilibrium is considered in the deformed position, and the compatibility relationships are nonlinear. In this case, geometric nonlinearity is considered with no approximations.
- The third type is the P-Delta analysis. In this type, equilibrium is considered in the deformed position with some minor approximations, and the compatibility relationships are assumed to be linear. In this case, geometric nonlinearity is considered approximately.

P-Delta analysis is more efficient computationally than large displacements analysis. For most structures, it is a loss of computer time to consider for true large displacements. P-Delta effect is the additional overturning moments due to lateral movement of a story mass to a deformed position. The second order effect of vertical loads acting upon a laterally displaced structure is termed the P-Delta effect, where P is the total vertical load, and Delta is the lateral displacement relative to the ground. In reality, when horizontal loading acts on a building and causes it to drift, the resulting eccentricity of the gravity loading from the axes of the walls and columns produces additional external moments to which the structure responds by drifting further. The additional drift induces additional internal moments sufficient to equilibrate the gravity load moment, **Smith** and **Coull, 1991**.

To better understand the seismic-induced response of high-rise buildings, a plenty of studies have been carried out. Most recently, **Dhawale and Narule, 2016,** studied the P-Delta effect on high rise R.C. framed buildings with a different number of stories. All analyses (Linear static analysis without P-Delta effect and nonlinear static analysis with P-Delta effect) carried out in software SAP 2000-V12. The results showed that it is essential to consider the P-delta effect for 25 story building. **Pillai and Chandran, 2016,** focused on the effectiveness of P-Delta analysis in the design of tall slender reinforced concrete structures. The researchers analyzed building models with different story heights. The stability of tall structures to lateral forces with and without considering P-Delta effects is carried out using ETABS 2015 Structural analysis software. The results showed that the P-Delta effects significantly influence the displacement and have a higher value than linear static analysis and that P-delta is essential for stories higher than 15 stories. **Bondre and Gaikwad, 2016,** compared different methods in terms of their efficiency and accuracy to recognize in what way the P-Delta effects determine the variation of responses of the structure such as bending moments, displacements and shear forces against linear static analysis. They studied 12 cases for buildings with different heights. They performed linear static and P-Delta analysis separately using STAAD pro software. The results showed that P-Delta effects significantly influence the structural components and get a higher value than the linear static analysis.

2. OBJECTIVES OF THE STUDY

According to ASCE7-10, **ASCE7-10, 2010**, all structures shall be assigned to a Seismic Design Category (SDC) which is a classification assigned to a structure based on its Risk Category and the severity of the design earthquake ground motion at the site. This study aims to study the significance of P-Delta effects on the dynamic response of tall reinforced concrete buildings when assigned to different SDCs allowed by ASCE 7-10. To achieve this goal, the dynamic response of these buildings is examined due to a wide spectrum of earthquake ground motion forces, including minor earthquake up to moderate and strong earthquakes.

Moreover, dynamic response is examined for linear and nonlinear analyses with P-Delta effects using frequency domain analysis. Maximum story displacement, story drift, columns bending moments and shear forces were investigated for five building models with different heights and ground motion forces. The parameters adopted here include a number of building stories and the seismic design category assigned for response analysis.

3. PROBLEM ASSESSMENT

3.1 Description of Building Models

The finite element software ETABS "Extended 3D Analysis of Building Systems", **CSI, 2015**, is used in this research to investigate the structural behavior of the modeled reinforced concrete building prototypes. Building models adopted throughout the present study are essentially multi-story reinforced concrete buildings with a different number of stories**. Fig. 1** shows a typical view of the 3D model of the building and plans view of typical story details. The structural system has been assumed as a dual system consists of a central core of shear wall structure and interior and exterior columns arranged in a rectangular 6x6 meter grid and the exterior columns are connected by edge beam to form moment resisting frames in the two orthogonal directions. The plan of the multi-storey RC building is square 36 meter by 36 meters with columns and shear walls. The floor system for the building models has been assumed to be a reinforced concrete flat plate of 220mm thick. Five buildings models with a different number of stories and heights have been adopted including; ten (G+9), twenty (G+19), thirty (G+29), forty (G+39), and fifty (G+49) stories.

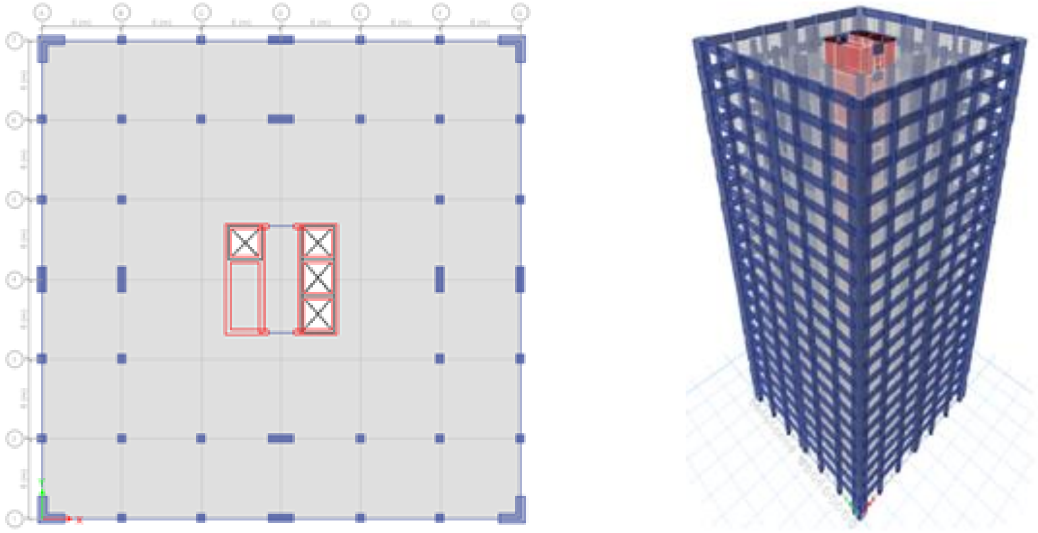


Figure 1. Typical view of the building 3D model and a plan view of the typical story.

Table 1 shows loads data and parameters for gravity loads, and dynamic seismic load cases respectively. On the other hand, **Table 2** present section properties for the columns and shear walls for the five-building prototypes and for all stories where C1 represent the square columns, C2 represent the corner columns, and C3 represents the rectangular columns. All beams have been assumed to have 30 cm by 110 cm cross-section and coupling beams between shear walls have been assumed to have 110 cm depth and the same thickness of shear walls that make up the central core. Section properties shown in **Table 2** were based on strength and serviceability requirements stipulated in the relevant specification, **ASCE 7-10, 2010**.

Table 1. Loading data.

Load Name	**Load Type**	**Details**	**Value**
Dead	Dead Load	Self-Weight of Structural Members Calculate automatically using the self-weight multiplier in ETABS	-
		Imposed Load on Slab: (Finishing + Partition Load)	3 kN/m2
		Uniform Load on Beams: (Line Load)	10 kN/m
Live	Live Load	Uniform Load on Slab for roof	2 kN/m2
		Uniform Load on Slab for floors	3 kN/m2

Table 2. Section properties for building models.

Building Model	**Story**	**The dimension of columns (cm)**			**shear wall thickness (cm)**	**Concrete strength***
		C1	**C2**	**C3**		
G+9	G to 9	70x70	L 200x70	200x70	40	C40
G+19	G to 9	80x80	L 200x80	200x80	45	C50
	10 to 19	70x70	L 200x70	200x70	45	C40
G+29	G to 9	90x90	L 300x50	200x80	50	C50
	10 to 19	80x80	L 300x50	200x70	50	C50
	20 to 29	70x70	L 300x50	200x60	50	C40
G+39	G to 9	100x100	L 300x60	300x60	60	C60
	10 to 19	90x90	L 300x60	300x60	60	C50
	20 to 29	80x80	L 300x50	300x50	50	C50
	30 to 39	70x70	L 300x50	300x50	50	C40
G+49	G to 9	110x110	L 300x70	300x70	70	C70
	10 to 19	100x100	L 300x70	300x70	70	C60
	20 to 29	90x90	L 300x60	300x60	60	C60
	30 t0 39	80x80	L 300x60	300x60	60	C50
	40 to 49	70x70	L 300x50	300x50	50	C40

*** C** denotes the specified concrete compressive strength for 150mm cube at 28 days, expressed in N/mm^2

3.2 Analysis Procedure

Based on the structure's seismic design category (SDC), structural system, dynamic properties, and regularity the structural analysis for the seismic response evaluation permitted by the ASCE 7-10 shall consist of one of the types listed below:

1. Equivalent Lateral Force Analysis,
2. Modal Response Spectrum Analysis, and
3. Seismic Response History Procedure,

Equivalent lateral force analysis is a simple procedure uses an estimated fundamental period and the anticipated maximum ground acceleration, together with other relevant factors to determine maximum base shear. On the other hand, Modal Response Spectrum Analysis **(RSA)** is a more refined procedure in which the modal frequencies of the structure are analyzed in the frequency domain and then used with conjunction with earthquake design spectra to estimate the maximum modal response, **Paz, 2004**.

The response spectrum predetermined as one of the most acceptable and feasible techniques that deal with the applications of structural dynamics efficiently. Therefore, in order to investigate the role of different earthquake ground force intensities on the seismic response of tall RC buildings when P-delta effect included in the analysis, the seismic performance of high rise RC buildings is analyzed in this study using Modal Response Spectrum Analysis procedure (**RSA**). **Table 3** listed parameters adopted for seismic analysis applicable to response spectrum analysis.

Table 3. Parameters used for the dynamic response spectrum analysis**.**

Parameter	**Load Case**	
	Response Spectrum X	**Response Spectrum X**
Direction	X Dir.	Y Dir.
Diaphragm Eccentricity	0.05	
Seismic Coefficients	Ss, S1, and Long-Period Transition Period	
Seismic Design Category (SDC)	SDC A, SDC B, SDC C, and SDC D	
Soil Class	D	
Damping Ratio	0.05	

3.3 Seismic Analysis Data

Table 4 shows the seismic coefficients for the Seismic Design Categories (SDCs) and site class **D** implemented in the numerical analyses, while **Fig. 2** shows the design response spectrum for the adopted SDCs. The seismic spectral response acceleration parameters (S_S and S_1) are selected so that the seismic coefficients in **Table 4** represent average values for the corresponding SDC according to ASCE7-10.

Table 4. Seismic coefficients.

SDC	S_{DS}	S_{MS}	F_a	S_S	S_{D1}	S_{M1}	F_v	S_1
A	0.16	0.24	1.6	0.15	0.064	0.096	2.4	0.04
B	0.312	0.468	1.56	0.3	0.128	0.192	2.4	0.08
C	0.41	0.615	1.464	0.42	0.187	0.278	2.32	0.12
D	0.533	0.800	1.312	0.61	0.258	0.388	2.04	0.19

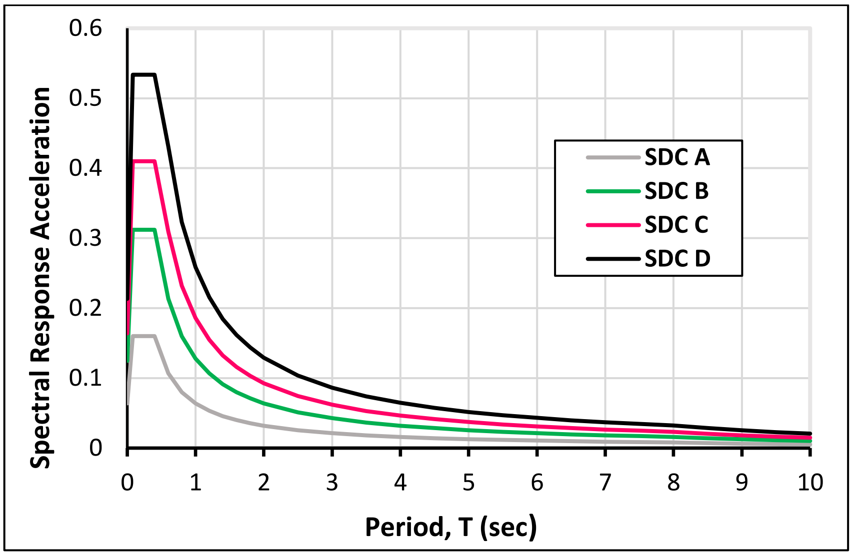


Figure 2. Response spectrum curves for SDC A, SDC B, SDC C, and SDC D.

4. ANALYSES RESULTS

In the following summary of the analyses results for the different building models due to different earthquake ground excitations to highlight the influence of the P-Delta effects on the dynamic response of high rise reinforced concrete buildings. Results are presented in terms of story displacements, story drifts, column moment and column shear.

4.1 Stability and P-Delta Effect

In building code for minimum design loads for buildings and other structures, **ASCE7-10**, **2010,** P-Delta effects on story shears and moments, the resulting member forces and moments, and the story drifts induced by these effects need not to be considered where the stability coefficient (θ) as determined by Eq. (1) is equal to or less than (0.10):

$$\theta = \frac{P_x \, \Delta \, I_e}{V_x h_{sx} C_d} \qquad (1)$$

where:

P_x = the total vertical design load at and above Level x, where computing P_x, no individual load factor need exceed 1.0

Δ = the design story drift occurring simultaneously with V_x

I_e = the importance factor.

V_x = the seismic shear force acting between Levels x and x – 1.

h_{sx}= the story height below Level x.

C_d = the deflection amplification factor in Table 12.2-1 of the ASCE 7-10

The stability coefficient (θ) must not exceed θ_{max} determined as follows:

$$\theta_{max} = \frac{0.50}{\beta \, C_d} \leq 0.25 \qquad (2)$$

Where (β) is the ratio of shear demand to shear capacity for the story between levels (x) and (x – 1). This ratio is permitted to be conservatively taken as 1.0.

When the stability coefficient (θ) is greater than (0.10) but less than or equal to ($\theta_{\max}$). The incremental factor related to P-Delta effects on displacements and member forces shall be determined by rational analysis. Alternatively, it is permitted to multiple displacements and member forces by [1.0/ (1 – θ)]. Where (θ), is greater than ($\theta_{\max}$), the structure is potentially unstable and shall be redesigned, **ASCE7-10, 2010**.

In this study, section properties for building models compiled in **Table 1** were selected to satisfy strength and serviceability requirements. Accordingly, stability coefficient (θ) have been calculated for all building stories and the resulting maximum value for (θ) for each building model is shown in **Table 5**. It is observed that all building models satisfy the stability criterion for ASCE 7-10. Results for incremental factor [1.0/ (1 – θ)] related to P-Delta effects on displacements and member forces allowed by ASCE 7-10 to be compared with the calculated values for P-Delta effect shown in the following sections.

Table 5. Maximum stability coefficient (θ) for the adopted building models.

Building Model	**Stability coefficient (θ)**		**incremental factor, $(\frac{1}{1-\theta})$**
	X-Dir.	**Y-Dir.**	**X-Dir.**
G+9	0.0245	0.0148	2.50%
G+19	0.1006	0.0758	11.25%
G+29	0.1398	0.128	16.20%
G+39	0.1695	0.1629	20.40%
G+49	0.2334	0.2309	30.40%

4.2 Buildings Displacement and Story Drift

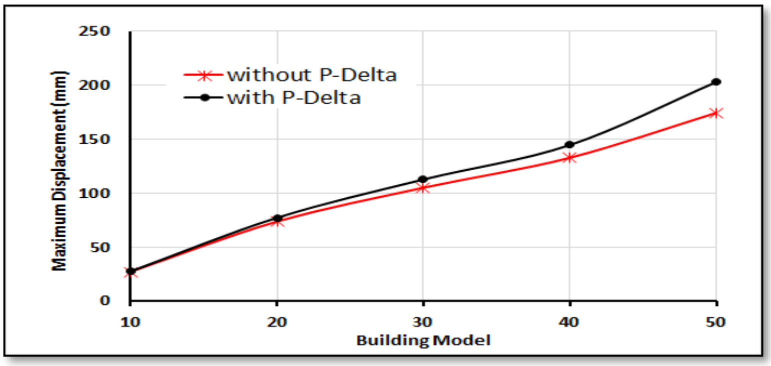
This subsection summarizes models' responses in terms of building's top displacement and story drift. **Table 6** shows results of top story displacement and maximum story drift, respectively, for linear and nonlinear dynamic analyses for all building models and for different seismic design categories and the percentage increase in buildings sway and drift when P-Delta effects included in the analyses. **Fig. 3** and **Fig. 4** show schematically comparison between maximum top story displacement and maximum story drift, respectively, for cases of analyses of with and without P-Delta effects for SDC A, SDC B, SDC C, and SDC D.

These figures and tabulated values for all models response reveal that taller buildings display fewer oscillations than their shorter counterparts for a given time period and that peak values of response are, generally, greater for taller buildings. Moreover, the nonlinear response for building's sway and drift are larger as opposed to linear analysis and that percentage increase due to P-Delta effects are almost the same for each building height irrespective of the seismic design category assigned to the building. Generally, buildings response in terms of lateral sway and story drift increases as P-Delta accounted for and as seismic excitation force, i.e. the seismic design category assigned, increased.

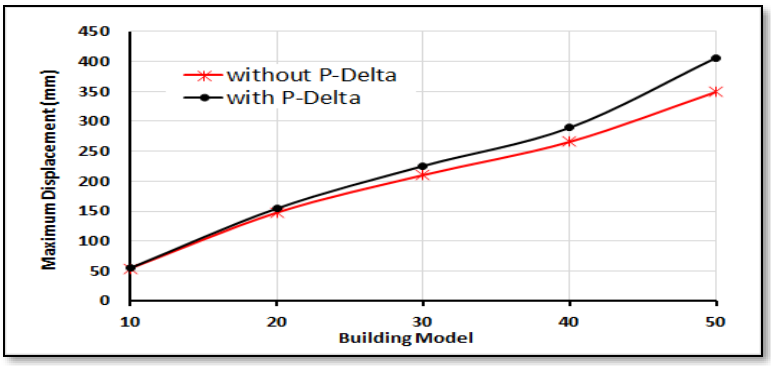
Finally, results presented indicate that for 10 story building the increase in building response due to P-Delta effects is around 1%, whereas an increase of about 5% to 16% is encountered for buildings with 20 stories and up to 50 stories.

Table 6. Top story displacement and maximum story drift for different SDC**.**

Building Model		**Top Story Displacement (mm)**			**Maximum Story Drift (mm)**		
SDC A							
Name	**No. of stories**	**Without P-Delta**	**With P-Delta**	**% difference**	**Without P-Delta**	**With P-Delta**	**% difference**
G+9	10	27.214	27.522	1.13	3.265	3.296	0.94
G+19	20	73.775	77.264	4.73	4.574	4.805	4.81
G+29	30	105.156	112.79	7.26	4.404	4.712	6.54
G+39	40	132.937	144.742	8.88	4.204	4.574	8.09
G+49	50	174.614	203.152	16.34	4.528	5.221	13.27
SDC B							
Name	**No. of stories**	**Without P-Delta**	**With P-Delta**	**% difference**	**Without P-Delta**	**With P-Delta**	**% difference**
G+9	10	54.38	54.996	1.13	6.514	6.591	1.17
G+19	20	147.519	154.497	4.73	9.148	9.594	4.65
G+29	30	210.294	225.557	7.26	8.793	9.409	6.55
G+39	40	265.874	289.480	8.88	8.424	9.163	8.07
G+49	50	349.228	406.300	16.34	9.055	10.426	13.15
SDC C							
Name	**No. of stories**	**Without P-Delta**	**With P-Delta**	**% difference**	**Without P-Delta**	**With P-Delta**	**% difference**
G+9	10	78.6104	79.499	1.13	9.409	9.533	1.32
G+19	20	213.752	223.872	4.73	13.244	13.891	4.89
G+29	30	304.748	326.880	7.26	12.736	13.629	7.01
G+39	40	385.422	419.654	8.88	12.197	13.275	8.84
G+49	50	506.369	589.134	16.34	13.121	15.123	15.26
SDC D							
Name	**No. of stories**	**Without P-Delta**	**With P-Delta**	**% difference**	**Without P-Delta**	**With P-Delta**	**% difference**
G+9	10	109.248	110.479	1.13	13.075	13.244	1.29
G+19	20	297.312	311.401	4.74	18.403	19.312	4.94
G+29	30	424.142	454.942	7.26	17.71	18.973	7.13
G+39	40	536.523	584.170	8.88	16.986	18.48	8.8
G+49	50	704.981	820.208	16.34	18.264	21.052	15.27



SDC A



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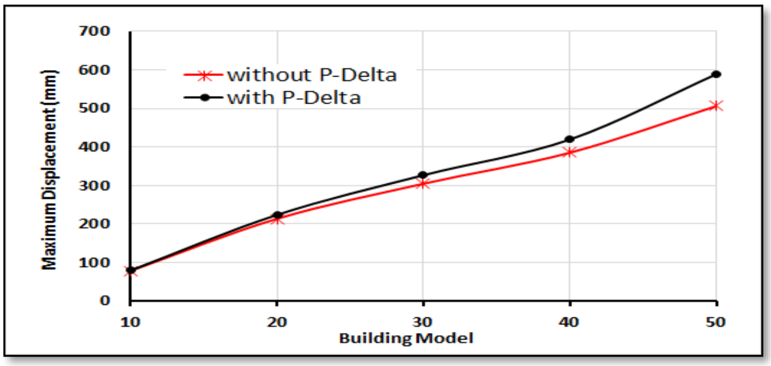

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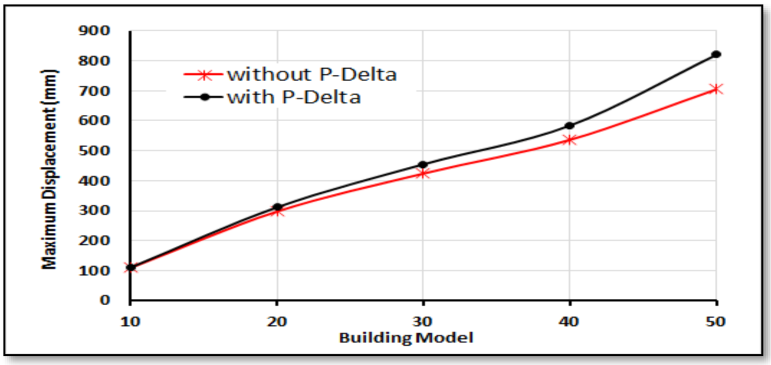

SDC D

Figure 3. Maximum story displacement for linear and nonlinear analyses.

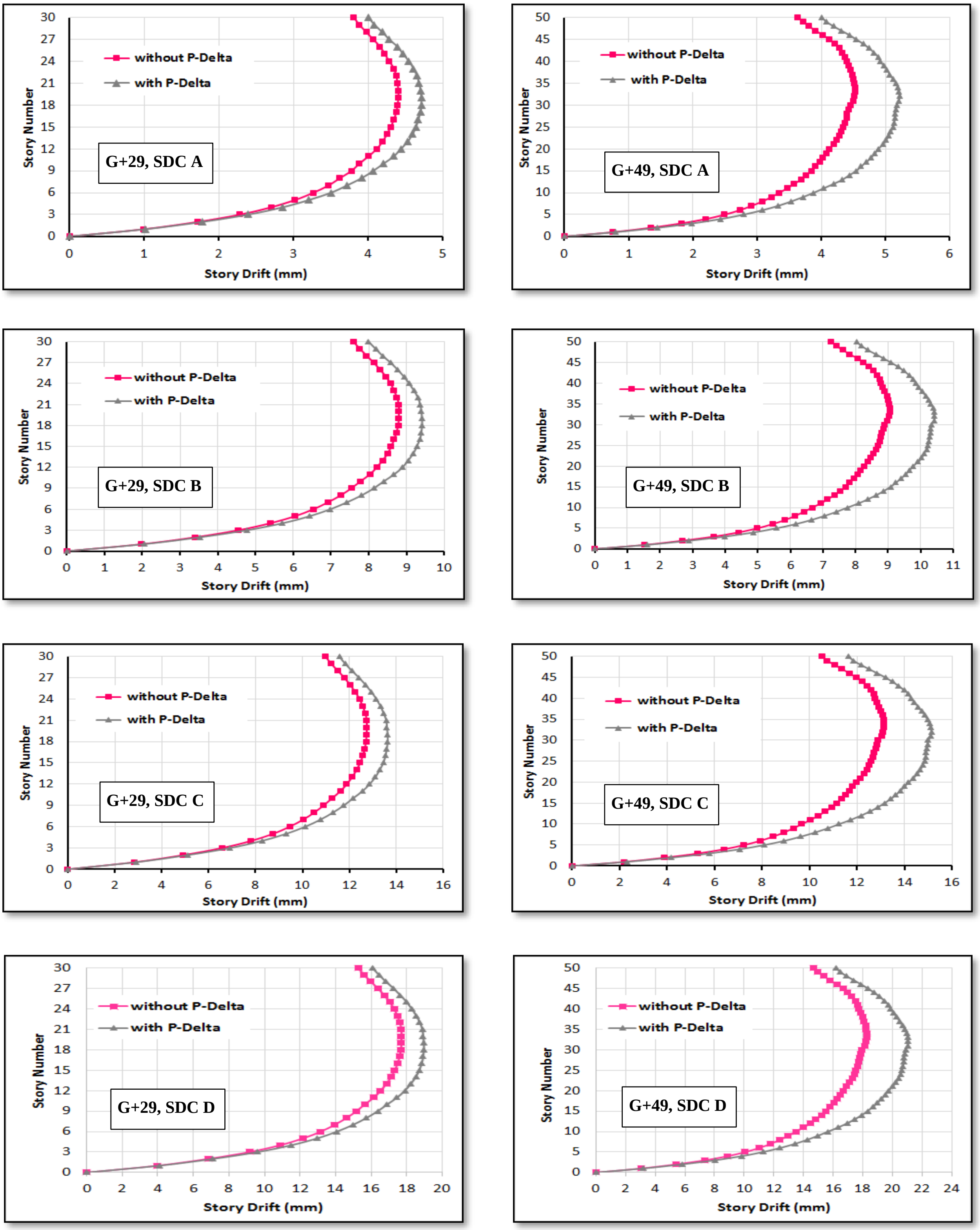

Figure 4. Buildings G+29 and G+49 story drift due to linear and nonlinear analyses.

4.3 Columns Moment and Shear Force

As in subsection 4.2, the same building models and analysis procedure are applied here with only one exception, an investigation for linear and nonlinear with P-Delta effects frequency domain analyses to focus on the effect of P-delta analysis on the response values for columns bending moments and shear forces. To achieve this goal, the column indicated in the plan of the building as shown in **Fig. 5** has been examined to determine the P-Delta effect when seismic forces due to different earthquake intensities applied in the X-direction.

Below are the graphs in **Fig. 6** for the five-building models and for different SDC depicting results of column bending moment variation due to P-Delta effect when analyzed under linear and nonlinear frequency domain analyses. The same results shown in these figures are compiled in **Table 7** in which the variation percentage in column bending moment and shear force when P-Delta effects included in the analyses are presented.

Column moment results presented in **Fig. 6** and **Table 7** illustrate that nonlinear P-Delta analysis yields larger response values and, generally, column moment increases when P-Delta effects accounted for in the analysis. Generally, 10 story building exhibit the least increase in column moment due to P-Delta effects and that for taller building up to 50 stories a maximum increase of about 8% in column moment is encountered. Results presented reveal that there is no general trend for the percentage increase variation to be expected regarding different seismic design categories (SDC) implemented in the analyses.

As for column base shear results, **Table 8** demonstrates that column base shear due to nonlinear analysis is, generally, smaller than that of linear analysis. This result might be attributed to the fact the more flexible buildings' structure it becomes due to nonlinear behavior and the more time it requires to complete a cycle of lateral sway which leads to decrease of base shear values. Generally, a maximum decrease in column base shear values of about 8% is observed. As for moment values, shear results indicate that no general trend for the percentage variation to be expected due to different seismic design categories (SDC) implemented in the analyses.

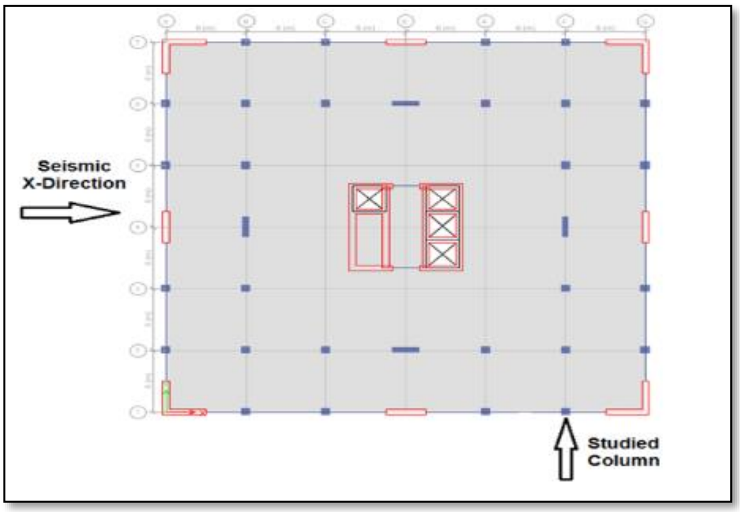

Figure 5. Location of the studied column.

Table 7. Column bending moment and shear force for different SDC**.**

Building Model		**Column Bending Moment (kN.m)**			**Column Shear Force (kN)**		
SDC A							
Name	**No. of story**	**Without P-Delta**	**With P-Delta**	**% difference**	**Without P-Delta**	**With P-Delta**	**% difference**
G+9	10	22.97	22.94	-0.08	7.46	7.21	-3.41
G+19	20	67.63	68.03	0.59	14.84	13.61	-8.32
G+29	30	119.52	126.66	5.97	32.94	33.06	0.36
G+39	40	188.71	199.85	5.9	44.81	44.25	-1.24
G+49	50	304.13	328.35	7.96	61.76	60.60	-1.88
SDC B							
Name	**No. of story**	**Without P-Delta**	**With P-Delta**	**% difference**	**Without P-Delta**	**With P-Delta**	**% difference**
G+9	10	44.39	44.73	0.75	14.42	14.04	-2.61
G+19	20	109.34	116.96	6.97	23.93	23.37	-2.32
G+29	30	215.33	217.64	1.08	59.57	56.79	-4.66
G+39	40	324.63	343.06	5.68	77.08	75.95	-1.48
G+49	50	572.35	588.64	2.85	117.01	108.64	-7.15
SDC C							
Name	**No. of story**	**Without P-Delta**	**With P-Delta**	**% difference**	**Without P-Delta**	**With P-Delta**	**% difference**
G+9	10	69.64	70.92	1.83	22.56	22.21	-1.57
G+19	20	145.53	154.79	6.36	31.79	30.86	-2.91
G+29	30	273.40	288.38	5.48	75.18	75.05	-0.17
G+39	40	428.66	452.49	5.56	101.66	100.03	-1.61
G+49	50	753.74	773.73	2.65	154.23	142.79	-7.41
SDC D							
Name	**No. of story**	**Without P-Delta**	**With P-Delta**	**% difference**	**Without P-Delta**	**With P-Delta**	**% difference**
G+9	10	103.17	105.82	2.57	33.37	33.08	-0.86
G+19	20	191.67	203.36	6.1	41.76	40.43	-3.18
G+29	30	358.14	377.16	5.31	98.35	97.99	-0.36
G+39	40	584.19	590.21	1.03	139.10	130.35	-6.29
G+49	50	978.99	1007.08	2.87	200.11	185.85	-7.13

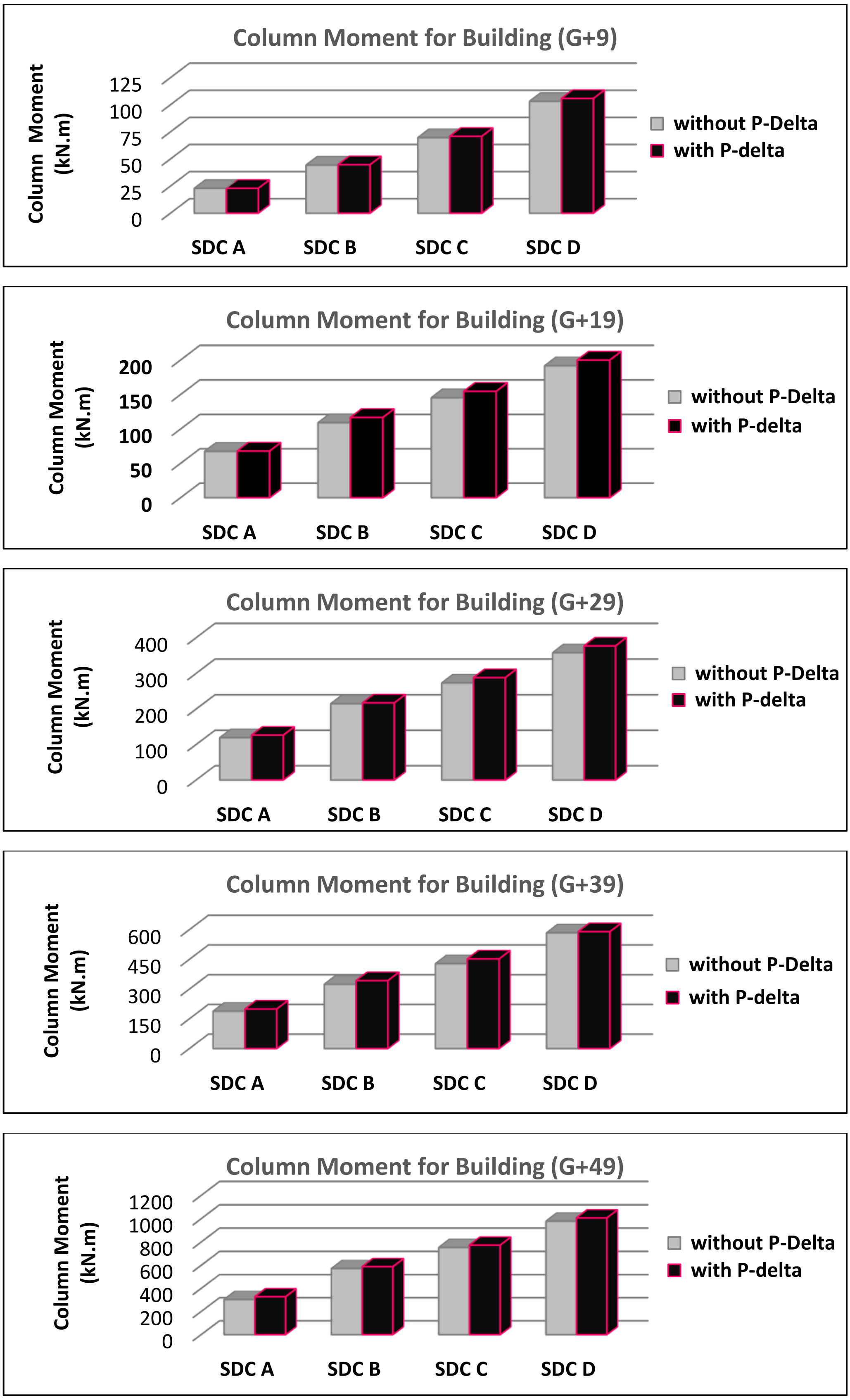

Figure 6. Column bending moment for linear and nonlinear analyses.

5. CONCLUSIONS

In this paper, an attempt was carried out to investigate the role of the seismic design categories permitted by ASCE 7-10 on P-Delta effects when accounted for in the seismic response of high-rise reinforced concrete buildings. According to comprehensive analyses, the following conclusions can be drawn:

1. Results showed that taller buildings display fewer oscillations than their shorter counterparts and that peak values of response are, generally, greater for taller buildings.
2. Generally, buildings response in terms of lateral sway and story drift increases as P-Delta effect accounted for and as seismic excitation force increased.
3. The percentage increase in building's lateral sway and story drift due to P-Delta effects is almost constant for certain building height irrespective of the seismic design category assigned to the building.
4. Results presented indicated that for 10 story buildings the effect of P-Delta can be neglected, whereas P-Delta effects are significant for buildings with 20 stories or more and need to evaluate by any analysis and design procedure.
5. The study shows that columns bending moment increases and shear force decreases when P-Delta effects accounted for in the analysis.
6. The study recommended that the effects of P-Delta need to be accounted for all SDCs allowed and the most important factor for P-Delta effects is the building height limit.
7. The incremental factor [1.0/ (1 – θ)] related to P-Delta effects on displacements and member forces allowed by the ASCE 7-10 yields conservative values.

6. NOMENCLATURE

F_a = short-period site coefficient (at 0.2 sec-period)
F_v = long-period site coefficient (at 1.0 sec-period)
SDC = Seismic design category according to ASCE7-10
S_{DS} = design, 5 percent damped, spectral response acceleration parameter at short periods
S_{MS} = the MCER, 5 percent damped, spectral response acceleration parameter at short periods adjusted for site class effects
S_S = mapped MCER, 5 percent damped, spectral response acceleration parameter at short periods
S_{D1} = design, 5 percent damped, spectral response acceleration parameter at a period of 1 sec
S_{M1} = the MCER, 5 percent damped, spectral response acceleration parameter at a period of 1 s adjusted for site class effects
S_1 = mapped MCER, 5 percent damped, spectral response acceleration parameter at a period of 1 sec.

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