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PERFORMANCE-BASED PLASTIC DESIGN OF EARTHQUAKE FOR SPECIAL MOMENT REINFORCED CONCRETE FRAMES CONSIDERING SOIL-PILE-STRUCTURE-INTERACTION

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ملخص البحث

طريقة التصميم اللدن القائم على الأداء (PBPD) شاع إستخدامها مؤخراً فى التصميم الزلزالى للمنشآت. تستهدف هذه الطريقة إزاحة أفقية و آلية الحركة عند الوصول الى حمل الخضوع للمنشأ, و هما قيم مختارة سلفاً قبل البدأ فى التصميم. فى هذا البحث تم تحليل إطارات من الخرسانة المسلحة المقاومة للعزوم و ذات ممطولية كافية, و ذلك طبقاً للكود الأمريكى ACI-318/ASCE-07 و أيضاً بطريقة (PBPD) . على الجانب الأخر, تم دمج النماذج الخاصة بالإطارات مع هامات خوازيق و خوازيق, لدراسة التأثير المتبادل بين التربة و الخوازيق و المنشأ (SPSI) . نتائج النماذج ذات الركيزة الثابتة و الأخرى ذات الركيزة المرنة الممثلة للخوازيق إستخدمت لدراسة المتغيرات مثل: الزمن الدورى, قدرة المنشأ على تحمل الأحمال الجانبية, و الإزاحة الأفقية و النسبية للأدوار.

ABSTRACT

Performance-Based Plastic Design (PBPD) method is widely extended for seismic design of building structures. A pre-selected target drift and yield mechanisms is used as key performance objectives. In this research, reinforced concrete special moment frames (RC SMF) were analyzed for high-rise concrete structures. Two designs were considered in the analysis, one design according to ACI-318/ASCE-07, and the other according to PBPD. RC SMF was also combined with pile caps and piles foundation system to provide a soil-pile-structure-Interaction (SPSI) model. Nonlinear lateral load-transfer from the foundation to the soil is modeled using p-y curves for soft clay soil that was considered in this study. Numerical results obtained using soil-pile-structure-interaction model conditions were compared to those corresponding to fixed-base support conditions, such as fundamental time period, structural capacity, story displacement and story drift.

KEYWORDS: Performance-Based Plastic Design (PBPD); Reinforced Concrete Special Moment Frames (RC SMF); Soil-Pile-Structure Interaction (SPSI); P-Y Curve; Pushover Analysis.

1. INTRODUCTION

Performance-Based Plastic Design (PBPD) method was derived from the Performance based Seismic design PBSD method. Performance-based Plastic design method starting from the pre-defined performance objectives, in which the intended yield mechanism is achieved through performing plastic design. Plastic design controls drift and yielding of frame members from the beginning to minimize the lengthy iterations to reach the final design [1-7].

Soil-structure-interaction (SSI) analysis simulates the combined response of the three connected systems: structure, foundation, and soil supporting the foundation. The ratio, $h / (V_s T)$, is the structure-to-soil stiffness ratio, and can be used to determine when the soil-structure-interaction effect is significant, such that, h is approximately two-thirds of the building height, this height represents the center of mass height for the first mode shape, V_s is shear wave velocity of the soil, and T is the fundamental time period of the structure with fixed-base supports [8]. Soil-structure-interaction can lengthen the structure time period significantly when structure-to-soil stiffness ratio exceeds 0.1, the change in time period will directly change the design base shear, compared with fixed-base analysis [8 and 9]. In some cases, at which the increase in time period due to soil-structure-interaction causes an increase in spectral acceleration, the SSI effect must be evaluated [10].

The numerical model that simulates the soil resistance to lateral displacement as predefined nonlinear springs is called p-y curve, where p is the soil pressure per unit length of the pile and y is the pile lateral deflection. The soil is represented by a series of nonlinear p-y curves that vary with depth and soil type. The p–y curves are used to relate pile deflections to the nonlinear soil reactions [11-13].

The Matlock theory [11] is used for laterally loaded piles in soft clays to determine p-y curves as illustrated in Equations 1 and 2. Figure 1 presents the schematic shape of p-y curve for soft clay as per Matlock model. Nonlinear lateral load-transfer from the foundation to the soil is modeled using p-y curves generated by computer program PyPile v.0.6.3 for soft clay soil.

$$p = 0.5\, p_u \left(\frac{y}{y_c}\right)^{\frac{1}{3}} \;,\; \frac{y}{y_c} \le 8 \tag{1}$$

$$p = p_u \;,\; \frac{y}{y_c} > 8 \tag{2}$$

$$y_c = 2.5 \in_{50} D \tag{3}$$

where, ε_{50} is the strain which occurs at one-half the maximum stress on laboratory unconsolidated un-drained compression tests of undisturbed soil samples, and D is the pile diameter.

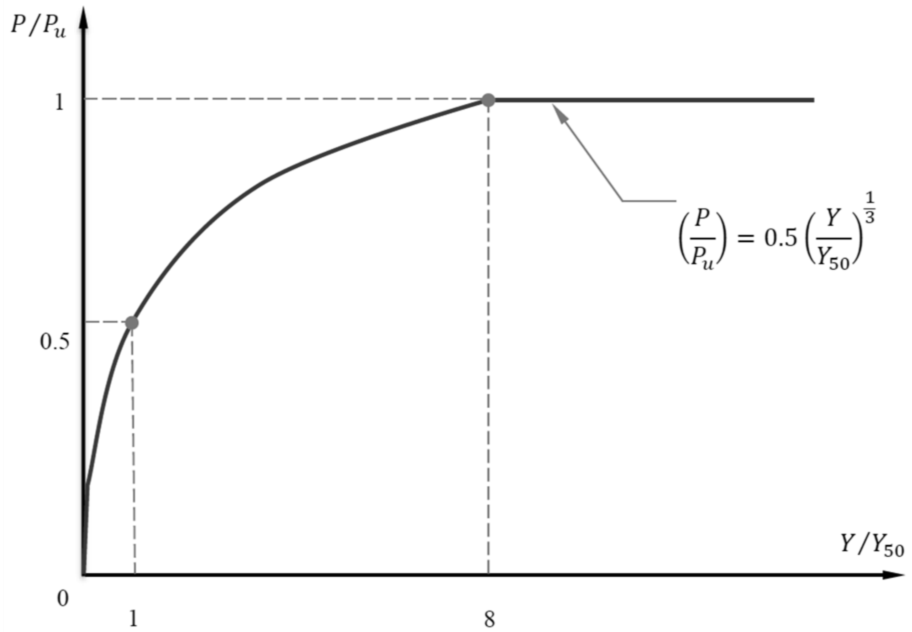

Figure 1: Soft clay (Matlock) model.

2. STATEMENT OF THE PROBLEM (PROBLEM FORMULATION)

Three baseline RC structures (8, 12 and 20-story internal RC special moment frame structure) as used in the FEMA P695 [14], was selected for this study. The frames are used to support both vertical and lateral loads. These (code-based design) structures were redesigned by the PBPD approach as shown in Table 1 [1]. The baseline structure and the PBPD structure were subjected to extensive inelastic pushover analysis, then tested considering soil-pile-structure-interaction (SPSI).

2.1. Input Data

The building is designed to sustain the following loading data:

- Design floor dead load = 8.38 kN/m^2 (175 psf).
- Design floor live load = 2.40 kN/m^2 (50 psf).

2.2. Material Properties

- Concrete cylinder compressive strength fc' = 34.5 - 41.4 MPa (5.0 - 6.0 ksi)
- Reinforcement rebar yield strength fy = 413.7 MPa (60.0 ksi)

2.3. Soil Properties

Soft clay soil is used for soil-pile-structure interaction modeling. Properties for this type of soil are as follow [15]:

- Dry Density = 17.50 kN/m^3
- Poisson's Ratio = 0.4
- Young's Modulus = 8 N/mm^2

Table 1: Building configuration and design parameters.

Design Parameters	8 - Story	12 - Story	20 - Story
ID Number	1012	1014	1021
Number of Floors	8	12	20
First Story Height m (ft)	4.572 (15)		
Upper Stories Height m (ft)	3.962 (13)		
Bay Size m (ft)	6.096 (20)		
Total Height m (ft)	32.309 (106)	48.158 (158)	79.858 (262)
Code Compliant Base Shear kN (kip)	418.1 (94)	547.1 (123)	907.4 (204)
PBPD Compliant Base Shear kN (kip)	632.5 (142.2)	746 (167.7)	1567.1 (352.3)

3. MODEL DESCRIPTION

SAP2000 v20 software analysis package was used in this study to perform pushover analysis. Twelve models were produced as described in Table 2. 2D-models were created for each case and P-Delta effect was considered in all of them - Figure 2. The foundation soil-pile system is modeled by replacing the support by thick shell elements representing pile cap supported on piles as indicated, and joined to link elements that simulates the soil resistance using p-y curves, in addition to a linear spring at the bottom end of the pile to provide a vertical support with elastic stiffness equals pile capacity divided by 0.01m as an accepted allowable settlement. For SPSI models, piles used were 20 and 25m long for the 8 and (12, 20) story buildings, respectively, and having a diameter of 1.0m and 1.2m for the (8, 12) and 20 story buildings, respectively.

Table 2: Analysis models produced.

Model Description	Design Following Code			Design Following PBPD		
	8	12	20	8	12	20
Without SPSI	√	√	√	√	√	√
With SPSI	√	√	√	√	√	√

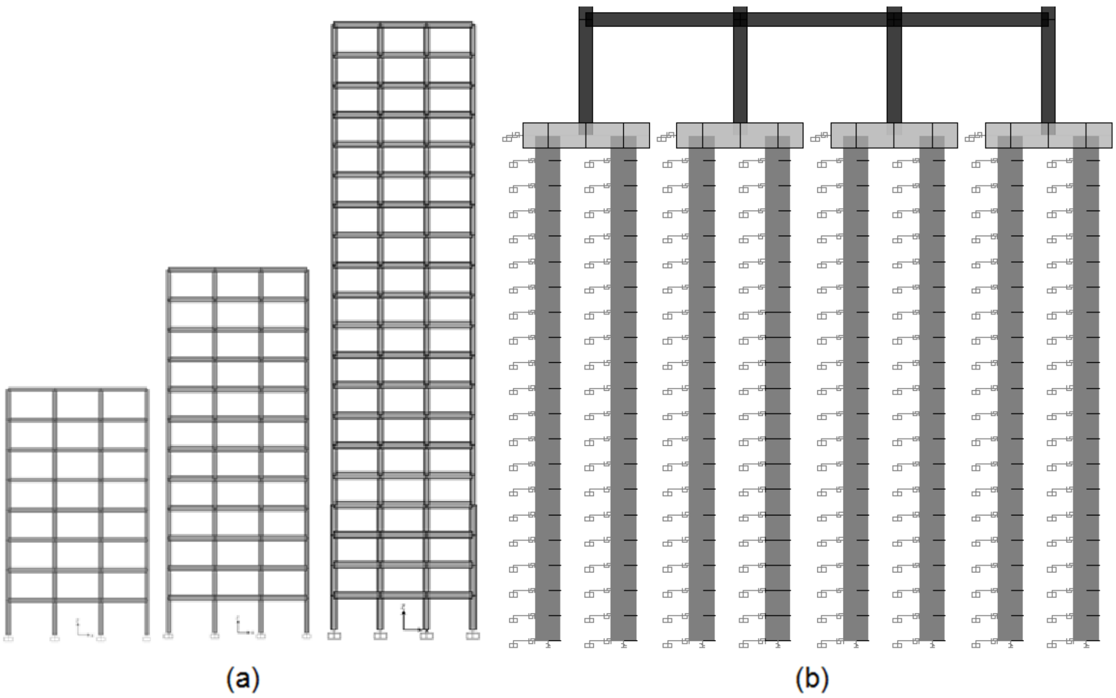

Figure 2: (a) SAP2000 2D-Model - Without SPSI. (b) SAP2000 2D-Model - With SPSI.

4. RESULTS AND DISCUSSION

4.1. Fundamental Time Period

Fundamental time period values for fixed base structures and structures with soil-pile-foundation system are listed in Table 3. Deep foundation is expected to provide a rigid support for the structure in the vertical direction, but the lateral stiffness of the system (soil-pile-foundation) is affected by the soil. The time period of frames used to study SPSI increased depending on structural flexibility (reflected by building height); The frames designed using PBPD showed a smaller increase in time period than frames designed following the code.

Table 3: Fundamental time period values of structures (seconds).

Model Description	Design Following Code			Design Following PBPD		
	8	12	20	8	12	20
Without SPSI	1.79	2.29	2.91	1.82	2.03	2.41
With SPSI	2.27	2.78	3.14	2.20	2.37	2.64
Percent increase	27 %	21 %	8 %	21 %	17 %	10 %

4.2. Drift and Displacement

The outputs of pushover analysis (P-Delta Curve) were used to compare changes in the inter-story drift and roof displacement. Maximum inter-story drift at structural capacity, and roof displacement at maximum base shear (reference to base) were collected, summarized and presented in Table 4 and Figures 3 and 4. Both inter-story drift and roof displacement were affected by the soil flexibility. Frames designed using PBPD were less affected by SPSI, in spite of having greater values in general than frames designed following code.

Table 4: Maximum inter-story drift ratios and roof displacement at maximum base shear.

Model Description	Design Following Code			Design Following PBPD		
	8	12	20	8	12	20
Max. Inter-story Drift						
Without SPSI	0.89%	0.86%	1.26%	1.87%	1.80%	1.67%
With SPSI	0.82%	0.92%	1.30%	1.88%	1.80%	1.70%
Max. roof displacement (m)						
Without SPSI	0.182	0.207	0.433	0.467	0.528	0.730
With SPSI	0.174	0.226	0.455	0.476	0.535	0.756

4.3. Capacity and Base Shear

As per FEMA 356 [10], structural performance level “Life Safety (LS)”, means the post-earthquake damage state in which significant damage to the structure has occurred, but some margin against either partial or total structural collapse remains. While structural performance level “Collapse Prevention (CP)”, means the post-earthquake damage state in which the building is on the verge of partial or total collapse. However, all significant components of the gravity-load-resisting system must continue to carry their gravity load demands. Structural performance levels for allowable drift shall not exceed 2% and 4% for LS and CP, respectively. In this study the allowable drift for CP will be limited to 3% only.

The P-Delta curves results from pushover analysis for all the 12 models, modified to be Base shear ratio versus Lateral drift ratio, are presented in Figures 5 and

6. Structural capacity at 2% drift ratio, 3% drift ratio and maximum capacity base shear are presented in Tables 5 and 6.

In general, (for fixed base frames) frame capacity for frames designed using PBPD is less than that for frames designed following code, and exceeds the targeted design base shear. When introducing SSI into the equation, capacity of all frames is depending on the soil flexibility.

Table 5: Structure capacity at 2% drift ratio and at 3% drift ratio of structures.

Model Description	Design Following Code			Design Following PBPD		
	8	**12**	**20**	**8**	**12**	**20**
	Structure capacity at 2% drift ratio					
Without SPSI	NR	NR	NR	685	812	1033
With SPSI	NR	NR	NR	685	812	1073
	Structure capacity at 3% drift ratio					
Without SPSI	NR	NR	NR	577	NR	NR
With SPSI	NR	NR	NR	577	NR	NR

NR = Not Reached, Structure did not maintain capacity to this drift ratio.

Table 6: Maximum capacity base shear of structures.

Model Description	Design Following code			Design Following PBPD		
	8	**12**	**20**	**8**	**12**	**20**
Without SPSI	876	982	1520	714	902	1770
With SPSI	870	973	1508	707	891	1763

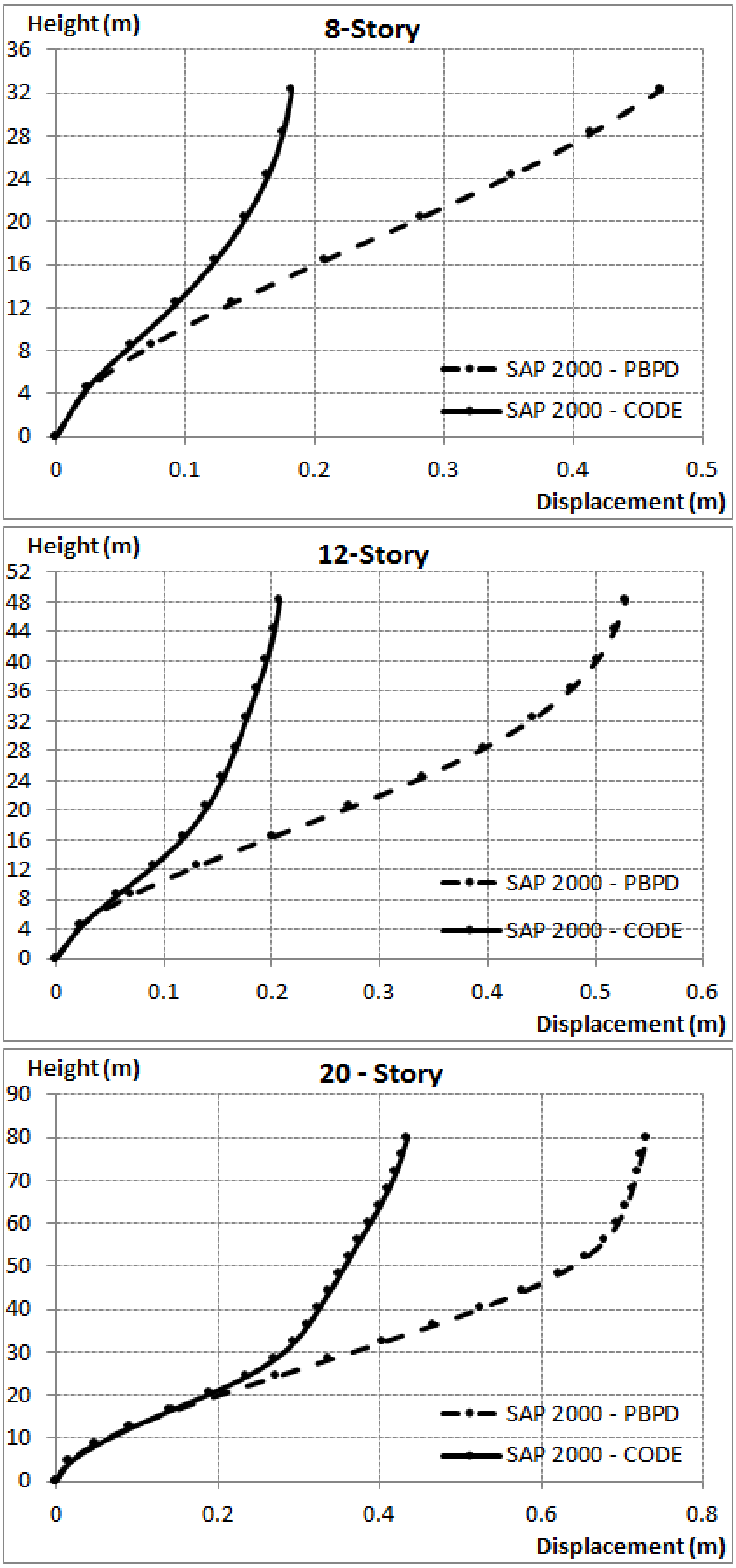

Figure 3: Floor Displacement - Without SPSI - Fixed-base support, for 8, 12 and 20 story.

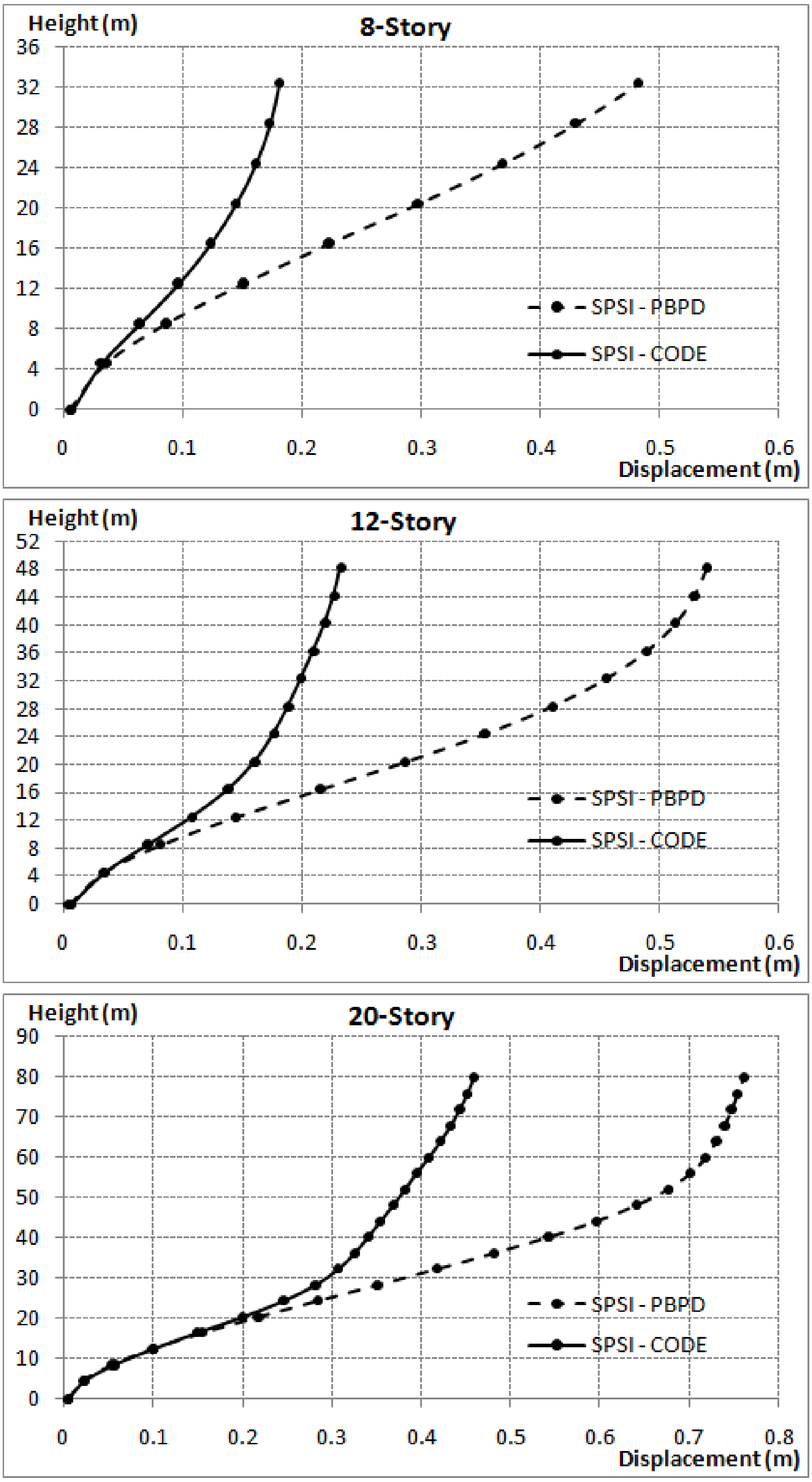

Figure 4: Floor Displacement - With SPSI, for 8, 12 and 20 story.

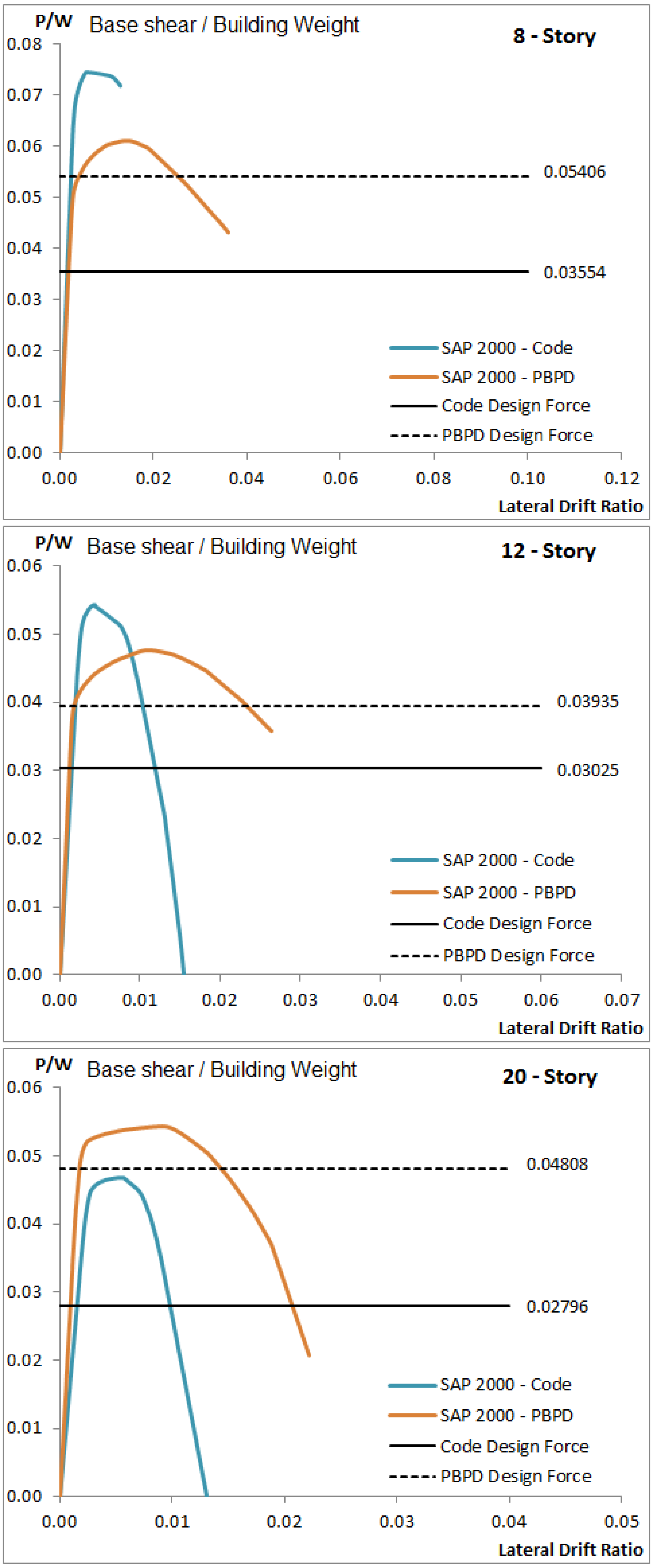

Figure 5: Base shear ratio versus Lateral drift ratio for fixed base, for 8, 12 and 20 story.

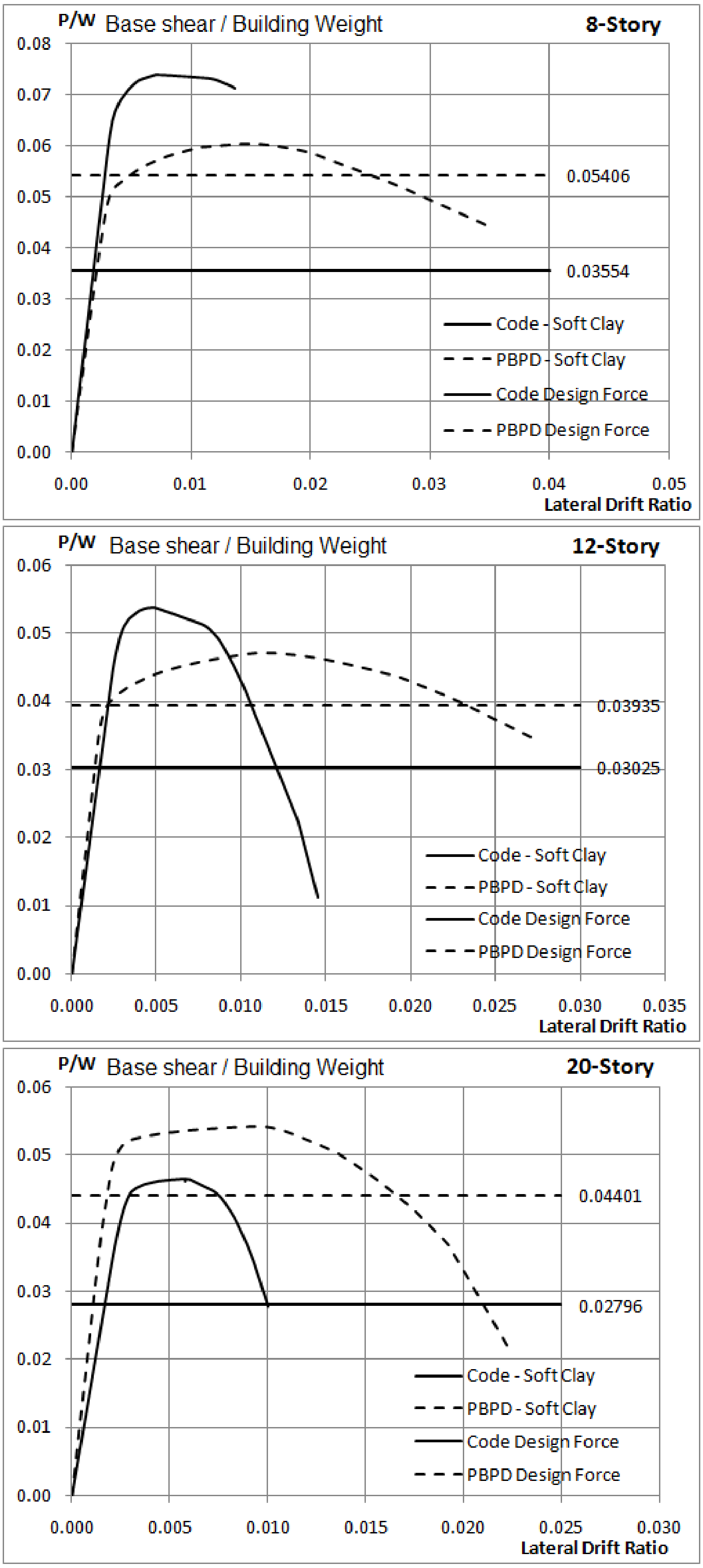

Figure 6: Base shear ratio versus Lateral drift ratio considering SPSI.

5. CONCLUSIONS

The PBPD method as a direct design method where the drift control and the selection of yield mechanism are initially assumed in the design work, proved that it is an effective method to reach a better performance for reinforced concrete moment resisting frames with fixed base support. It does not need lengthy iterations to achieve a suitable final design. On the other hand, considering soil structure interaction introduces other variables to the equation. SPSI can change the behavior of the fixed base structure.

This paper presents an assessment of the original code design and the PBPD methods to design RC SMF systems considering soil-pile-structure interaction. Main conclusions are as follows.

5.1. The natural Time Period

a. The natural Time Period varies significantly from the fixed base to the flexible base structure (considering SPSI).
b. Considering SPSI leads to an increase in time period.
c. Time period due to SPSI is increasing with the increase in building height; while period lengthening decrease with the increase of building height.

5.2. Drift and Displacement

a. Using PBPD method increases inter-story drift ratio.
b. Considering SPSI increases inter-story drift and roof displacement for both design methods.

5.3. Capacity and Base shear

a. PBPD can produce structures that meet preselected performance objectives in terms of yield mechanism and target drift.
b. Frame capacity designed using PBPD is generally less than that of code elastic design.
c. Considering SPSI reduces the capacity of frames designed following code elastic design and PBPD.
d. Frames with fixed base and designed following code elastic design failed to reach the 2% Life Safety drift limit and the 3% Collapse Prevention drift limit; While that designed following PBPD method reached a capacity exceeding the design base shear, except in the case of the 20-story structure. The 12-story structure almost reached the 3% drift limit reaching 2.8%.
e. At 2% life safety drift limit, frames designed using PBPD maintained its capacity, with minor loss in strength. When considering SPSI minor losses in strength occurs, except for the 20-story structure where major strength loss happens.
f. For models following code elastic design method, considering SPSI causes a significant loss in strength, ductility and do not reach the 3% drift limit. On the other hand, PBPD improves frames ductility but did not reach the 3% drift limit at the ultimate drift, except in the case of the 8-story structure.

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