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Original Empirical Research

Performance-Based Plastic Design of a Reinforced Concrete Frame for Seismic Loads Considering the Soil-Pile-Structure Interaction

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Abstract

Introduction. The authors make use of Performance-Based Plastic Design (PBPD) method that is commonly employed overseas for calculations and design of building structures in seismic hot spots. A pre-selected target drift and yield mechanisms is used as the key performance objectives. In this research, reinforced concrete special moment frames (RC SMF) were analyzed for high-rise concrete structures perceiving seismic loads.

Materials and Methods. Two designs were considered in the analysis, one 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.

Results. 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. Frames designed using PBPD were less affected by SPSI, in spite of having greater values in general than frames designed following the standards (codes).

Discussion and 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.

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

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Оригинальное эмпирическое исследование

Расчет железобетонного каркаса на сейсмические нагрузки с учетом взаимодействия системы «грунт-свая-конструкция» в нелинейной постановке

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Аннотация

Введение. В статье применен «метод пластического проектирования на основе эксплуатационных характеристик» (PBPD), который получил широкое распространение в зарубежной практике расчета и проектирования строительных конструкций в сейсмически опасных регионах. В качестве допустимых параметров используются предварительно выбранные значения смещений конструкций и текучести материалов. В данном исследовании были проанализированы специальные железобетонные «моментные» рамы (RC SMF) для высотных зданий, воспринимающих сейсмические нагрузки.

Материалы и методы. Для анализа рассматривалось проектирование двух вариантов конструкций: первый — в соответствии с международными стандартами ACI-318/ASCE-07, второй – в соответствии с методом PBPD. Каркас из железобетонных рам RC SMF был объединен с ростверком и системой свайных фундаментов для создания модели взаимодействия «грунт-свая-конструкция» (SPSI-модель). Нелинейная передача боковой нагрузки от фундамента к грунту моделируется с помощью кривых P-Y (нагрузка – перемещение) для мягкопластичного глинистого грунта, рассматриваемого в данном исследовании.

Результаты исследования. Численные результаты, полученные с использованием условий модели взаимодействия грунта со сваями, сравнивались с результатами, соответствующими условиям неподвижного основания, по таким факторам, как фундаментальный период, прочность конструкции, горизонтальные и вертикальные перемещения узлов на разных этажах. Рамы, спроектированные с использованием метода PBPD, были менее подвержены влиянию взаимодействия системы «грунт-свая-конструкция» SPSI, хотя в целом имели более высокие значения армирования, чем рамы, спроектированные по действующим нормам (кодам).

Обсуждение и заключение. Метод PBPD как метод прямого проектирования конструкций, при котором в расчетной схеме изначально предполагается контроль смещения конструкций, доказал, что он обеспечивает наиболее корректные параметры железобетонных рам, воспринимающих моменты от проектных нагрузок при задании неподвижной опоры здания.

Ключевые слова: пластическое проектирование на основе эксплуатационных характеристик (PBPD); железобетонные специальные моментные рамы (RC SMF); взаимодействие «грунт-свая-конструкция» (SPSI); кривая P-Y; анализ продавливания

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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 / (Vs T), is the structure-to-soil stiffness ratio, and can be used to determine when the soil-structure-interaction effect is significant so that h is approximately two-thirds of the building height, this height represents the center of mass height for the first mode shape, Vs 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 when 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. Fig. 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 the PyPile v.0.6.3 software program for soft clay soil.

$$p = 0{,}5p_u\left(\frac{Y}{Y_{50}}\right)^{\frac{1}{3}}, \frac{Y}{Y_{50}} \le 8 \quad (1)$$

$$p = p_u, \frac{Y}{Y_{50}} > 8 \quad (2)$$

$$Y_{50} = 2{,}5\varepsilon_{50}D\ . \quad (3)$$

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

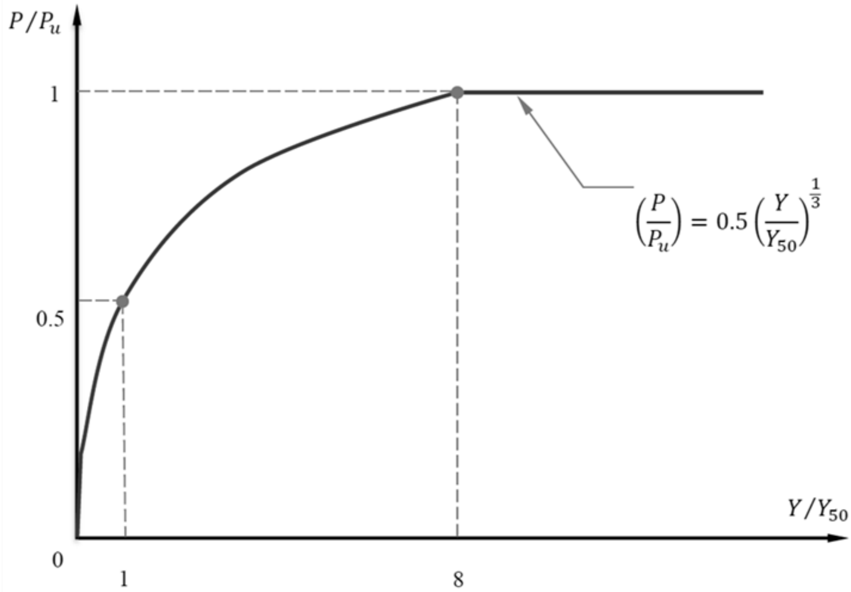


Fig. 1. Soft clay (Matlock) model

Materials and Methods

Statement of the Problem. Three baseline RC structures (8, 12 and 20-floor 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 means of 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).

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).

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)

Soil Properties

Soft clay soil is used for soil-pile-structure interaction modeling. Properties for this type of soil are as follows [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

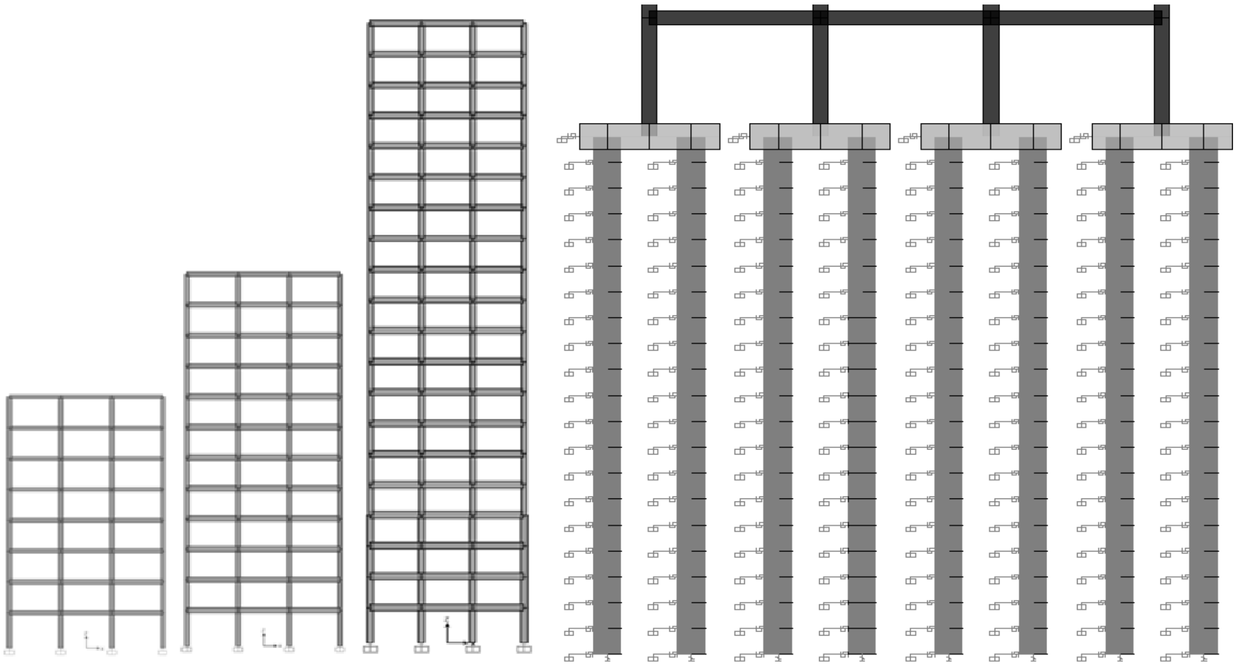
Design Parameters	8–floor	12–floor	20–floor
ID Number	1012	1014	1021
Number of Floors	8	12	20
First Floor Height, m (ft)	4.572 (15)		
Upper Floor Height, m (ft)	3.962 (13)		
Bay Size, m (ft)	6.096 (20)		
Total Height, m (ft)	32.309 (106)	48.158 (158)	79.858 (262)
Code Compliant Base Shear, kN (kip)	418.1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

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 (Fig. 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 0.01 m as an accepted allowable settlement. For SPSI models, the piles were 20 and 25 m long for the 8- and (12-, 20-) floor buildings, respectively, and having a diameter of 1.0 m and 1.2 m for the (8-, 12-) and 20-floor buildings, respectively.

Table 2

Analysis models produced

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



a) *b)*

Fig. 2. 2D-models *a* — SAP2000 2D-Model – Without SPSI;
b — SAP2000 2D-Model – With SPSI

Results

Fundamental Time Period. Fundamental time period values for fixed-base structures and those 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 the building height). The frames designed using PBPD showed a smaller increase in time period than those designed following the code.

Table 3

Analysis models produced

Model Description	Design Following					
	Code			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 %

Drift and Displacement. The outputs of pushover analysis (P-Delta Curve) were used to compare the changes in the inter-floor drift and roof displacement. The maximum inter-story drift at the structural capacity, and roof displacement at the maximum base shear (reference to the base) were collected, summarized and presented in Table 4 and Fig. 3 and 4. Both inter-floor 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 those designed following the code.

Table 4

Maximum inter-floor drift ratios and roof displacement at the maximum base shear

Model Description	Design Following					
	The Code			PBPD		
	8	12	20	8	12	20
Max. Inter-Floor 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

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 will 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 Fig. 5 and 6. The structural capacity at a 2% drift ratio, a 3% drift ratio and the maximum capacity base shear are presented in Table 5 and 6.

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

Table 5

Structural capacity at a 2% drift ratio and at a 3% drift ratio of the structures

Model Description	Design Following					
	The Code			PBPD		
	8	12	20	8	12	20
Structural capacity at a 2% drift ratio						
Without SPSI	NR	NR	NR	685	812	1033
With SPSI	NR	NR	NR	685	812	1073
Structural capacity at a 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 the capacity to this drift ratio						

Table 6

Maximum capacity base shear of the structures

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

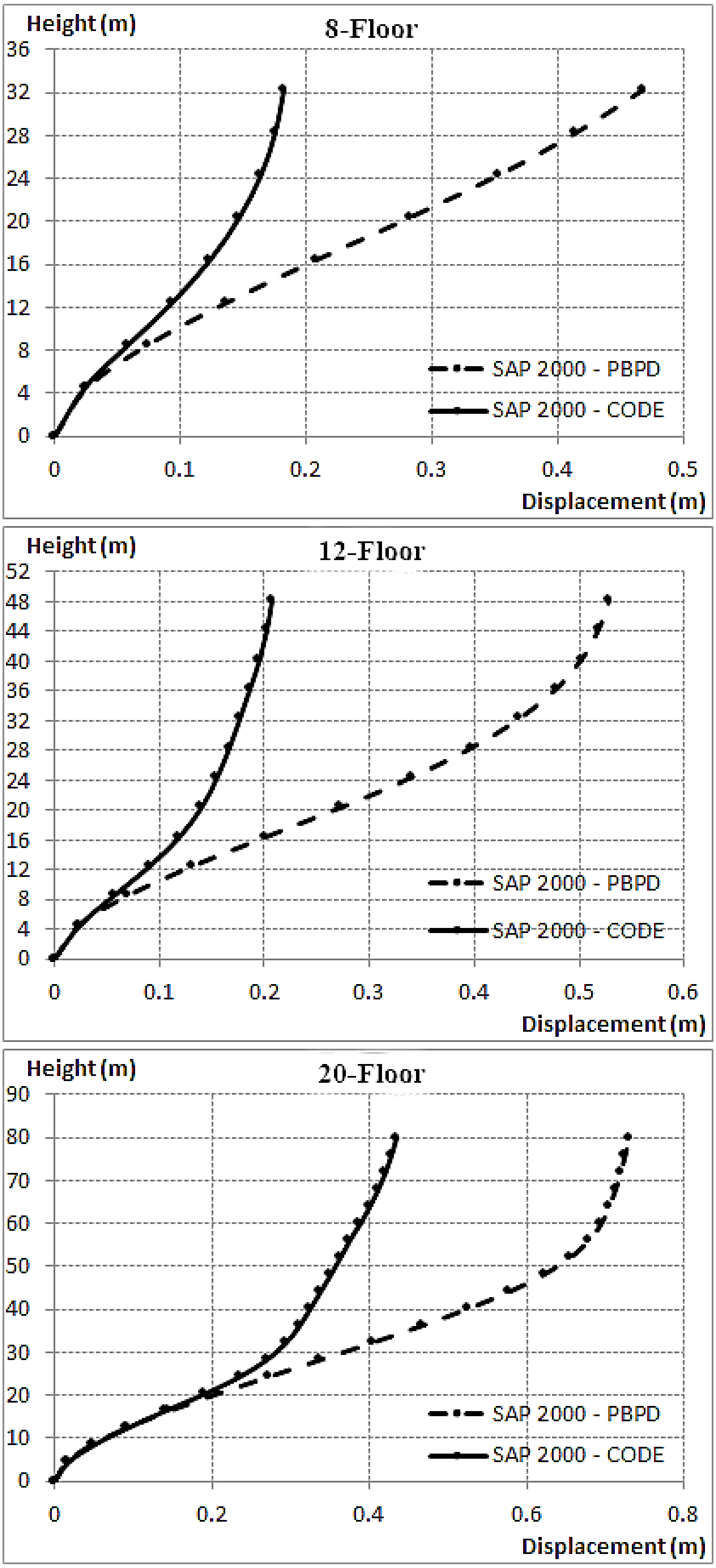


Fig. 3. Floor Displacement – Without SPSI – Fixed-base support, for 8-, 12- and 20- floor

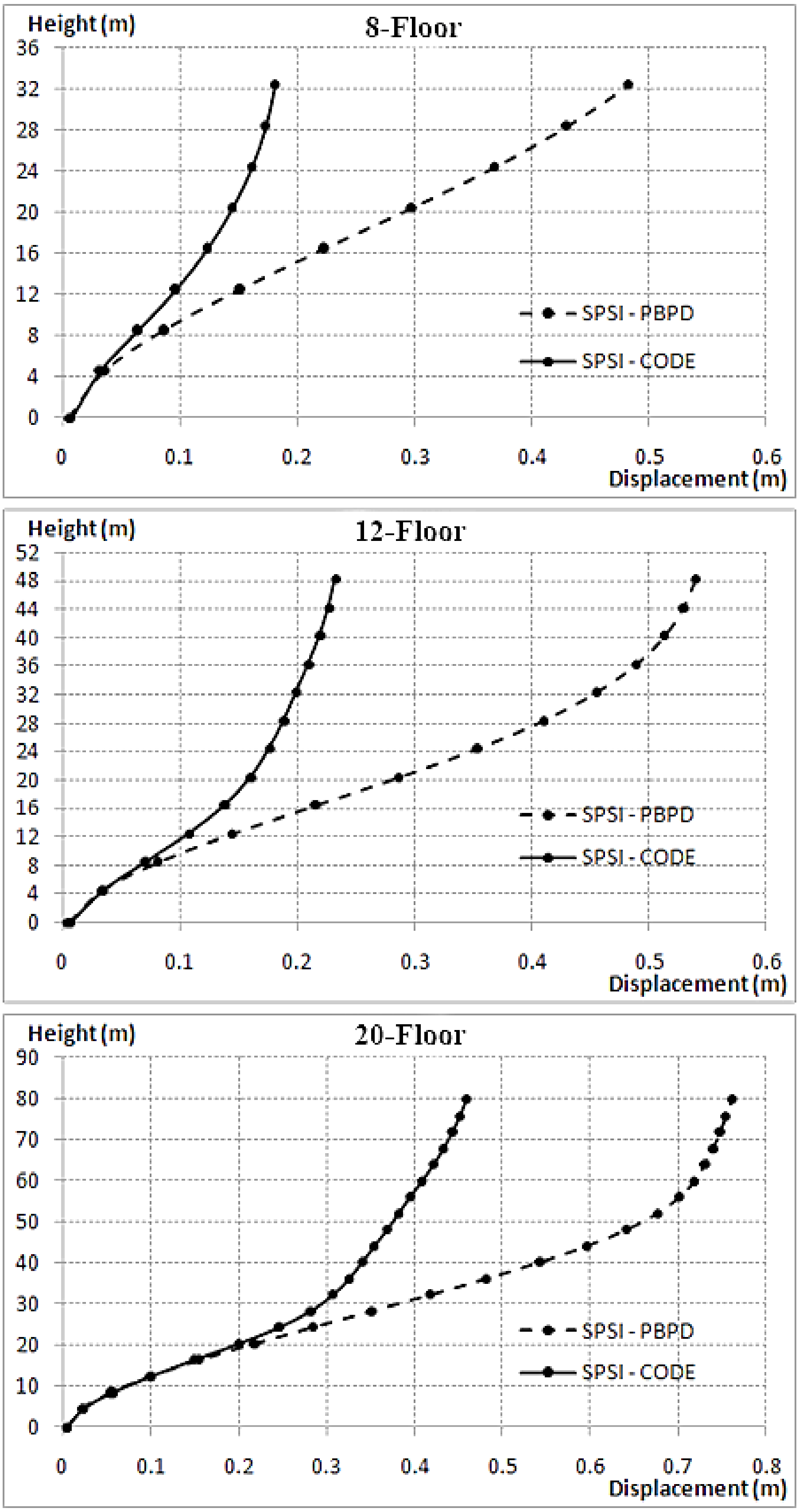


Fig. 4. Floor Displacement – With SPSI, for 8, 12 and 20 floor

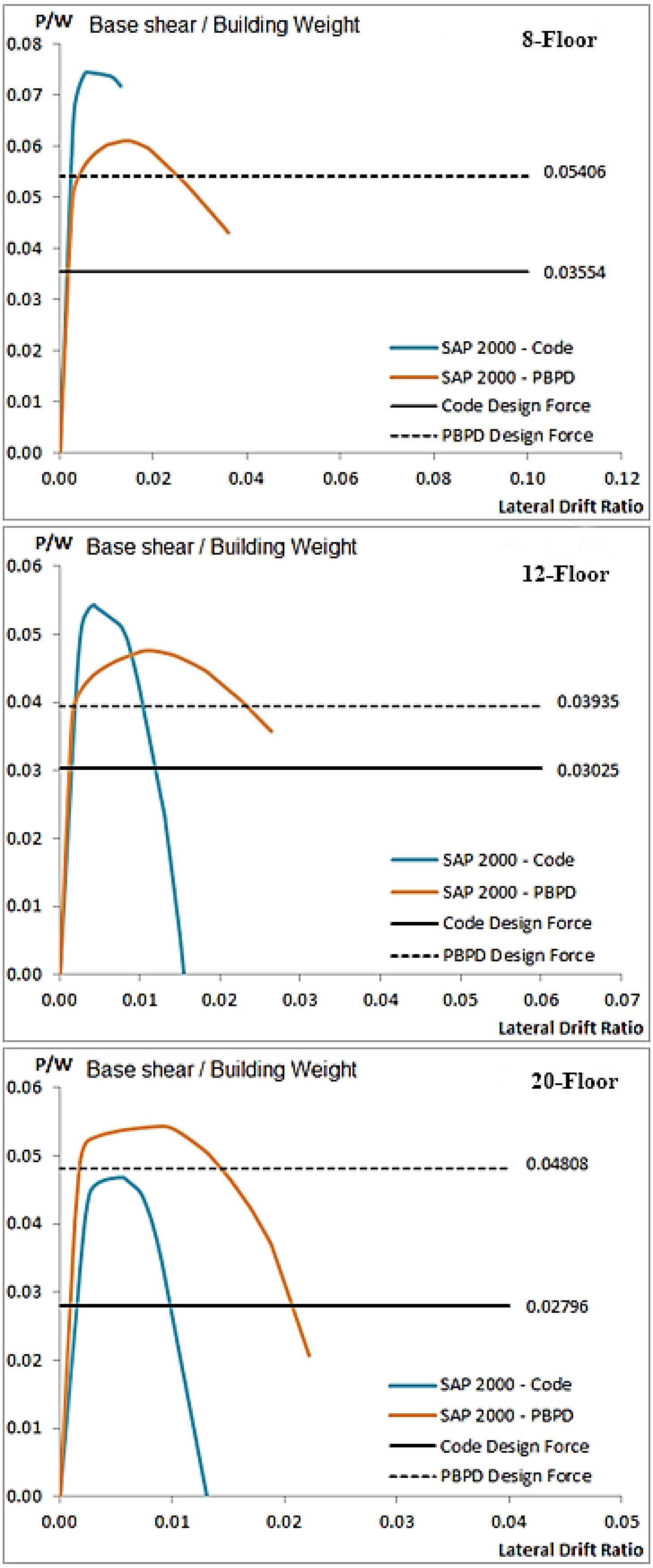


Fig. 5. Base shear ratio versus lateral drift ratio for a fixed base, for 8-, 12- and 20- floor

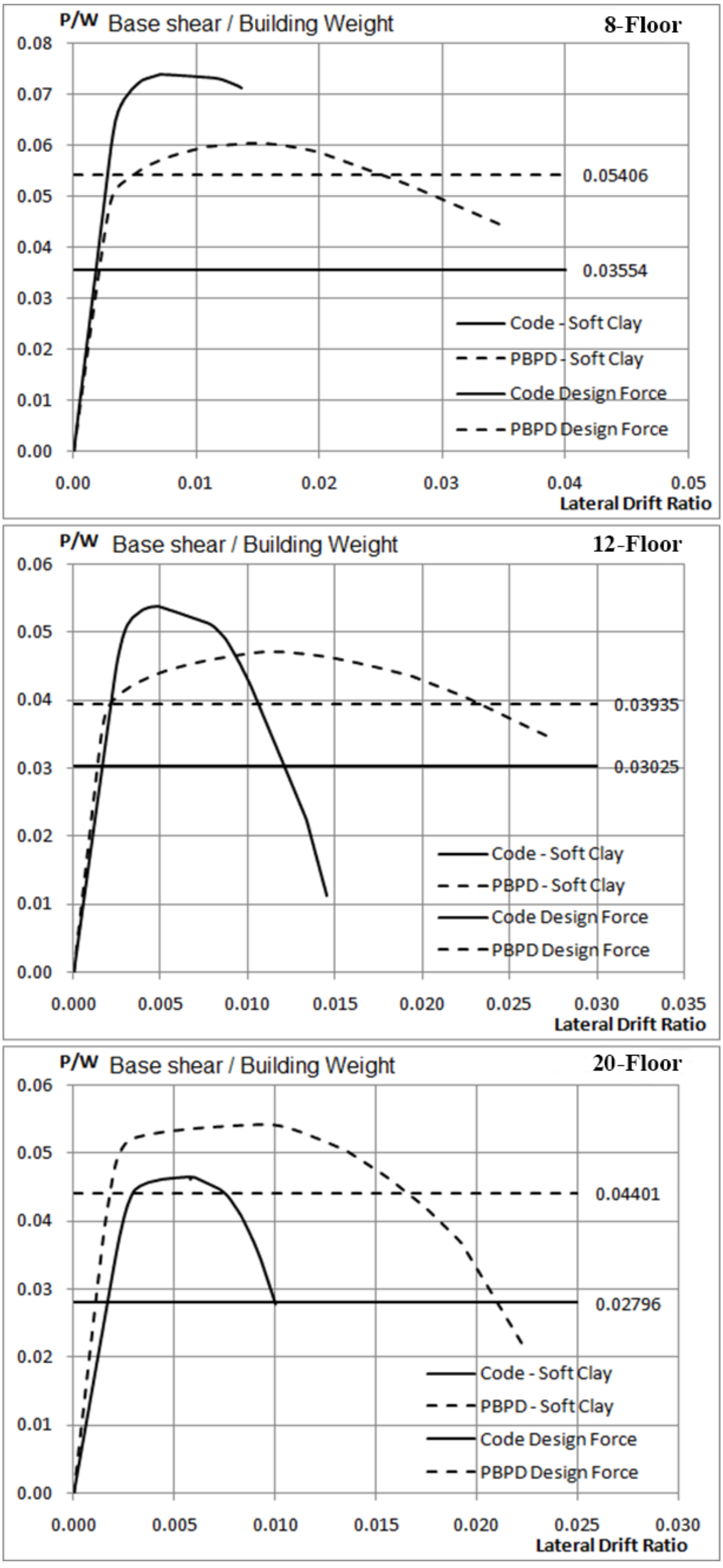


Fig. 6. Base shear ratio versus lateral drift ratio considering SPSI

Discussion and Conclusion. 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 a fixed-base support. It does not need lengthy iterations to achieve a suitable final design. On the other hand, considering the 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 the soil-pile-structure interaction. The main conclusions are as follows.

1. *The Natural Time Period*

– The natural time period varies significantly from a fixed-base to a flexible base structure (considering SPSI).

– Considering SPSI leads to an increase in time period.

– Time period due to SPSI increases as does the building height; while period lengthening decreases as the building height increases.

2. *Drift and Displacement*

– The use of the PBPD method increases an inter-floor drift ratio.

– Considering SPSI increases an inter-floor drift and roof displacement for both design methods.

3. *Capacity and Base shear*

– PBPD can produce structures that meet preselected performance objectives in terms of the yield mechanism and target drift.

– Frame capacity designed using PBPD is generally less than that of code elastic design.

– Considering SPSI reduces the capacity of frames designed following the code elastic design and PBPD.

Frames with a fixed base and designed following the code elastic design failed to reach the 2% Life Safety drift limit and the 3% Collapse Prevention drift limit, while the one designed following PBPD method reached a capacity exceeding the design base shear, except in the case of the 20-floor structure. The 12-floor structure almost reached a 3% drift limit reaching 2.8%.

At a 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-floor structure where major strength loss happens.

For models following the code elastic design method, considering SPSI causes a significant loss in strength, ductility and a 3% drift limit is not reached. On the other hand, PBPD improves the ductility of the frames but did not reach a 3% drift limit at the ultimate drift, except in the case of the 8-floor structure.

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Prokopov AYu: scientific guidance, formation of the basic concept, revision of the manuscript; formulation of the conclusions and recommendations.

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