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PERFORMANCE-BASED PLASTIC DESIGN OF EARTHQUAKE FOR LOW-RISE REINFORCED CONCRETE STRUCTURES CONSIDERING SOIL-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 نصف الفراغ المتجانس المعبر عن التربة, لدراسة التأثير المتبادل بين التربة و المنشأ (SSI). ستة أنواع من التربة تم دراستها فى هذا البحث, تشمل التربة الرملية و الطينية. نتائج النماذج ذات الركيزة الثابتة و الأخرى ذات الركيزة المرنة الممثلة للتربة 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 low-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 a homogeneous soil half-space to provide a simplified Soil-Structure-Interaction (SSI) model. Six types of clay and sandy soils were considered in this study. Numerical results obtained using soil-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-Structure Interaction (SSI); 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 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, where, 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 (SSI) 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 [8-12]. 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 [13].

The expression presented in Equation 1 is used to calculate the period lengthening due to SSI for multi-degree-of-freedom structures, applied only for the first-mode period to get flexible base time period, $T^{\sim}$ [8]. Base flexibility is divided into vertical, horizontal, and rotational flexibility represented by springs. This flexibility is accompanied by deflection when the structure is affected by lateral loads. Figure 1 illustrates these types of deformations, deflections and springs, where: k_z: vertical spring stiffness in z-direction, k_x: horizontal spring stiffness in x-direction calculated as per Equation 2, and k_{yy}: rotational spring in x-z plane (about y-y axis) Equation 3, k: building lateral stiffness considering fixed base, B, L, D, d_w and Z_w are defined in Figure 1, Aw: is the area of footing's vertical sides, ν: is soil Poisson's ratio, G: is shear modulus for soil, and I_y: is footing's moment of inertia about y-axis.

$$\frac{T^{\sim}}{T} = \sqrt{1 + \frac{k}{k_x} + \frac{k\,h^2}{k_{yy}}} \tag{1}$$

$$K_x = \left(1 + 0.15\sqrt{\frac{D}{B}}\right)\left[1 + 0.52\left(\frac{z_w A_w}{BL^2}\right)^{0.4}\right]\left[\frac{2GL}{2-\nu}\left[2 + 2.5\left(\frac{B}{L}\right)^{0.85}\right] - \frac{0.2}{0.75-\nu}GL\left[1 - \frac{B}{L}\right]\right] \tag{2}$$

$$K_{yy} = 1 + 0.92\left(\frac{d_w}{B}\right)^{0.6}\left[1.5 + \left(\frac{d_w}{B}\right)^{1.9}\left(\frac{B}{L}\right)^{-0.6}\right]\left[\frac{G}{1-\nu}\left(I_y\right)^{0.75}\left[3\left(\frac{L}{B}\right)^{0.15}\right]\right] \tag{3}$$

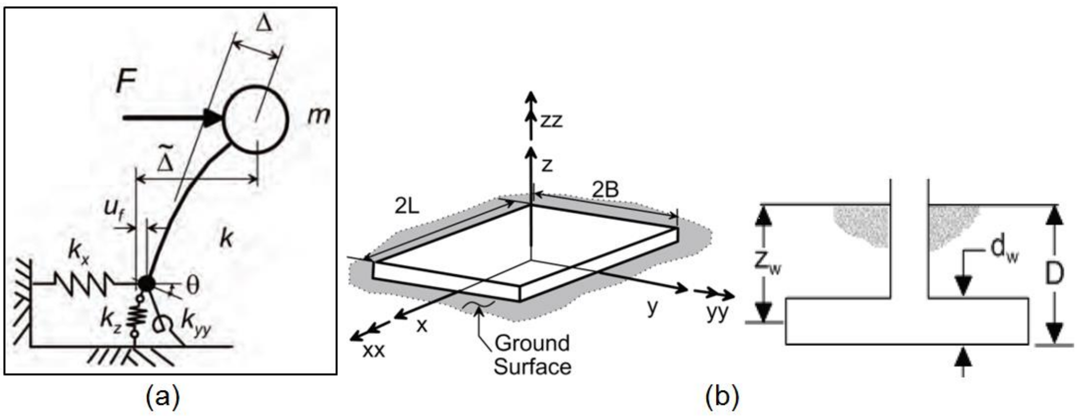


Figure 1: (a) Deflection illustration. (b) Illustration for equations 1,2 and 3. [2]

2. STATEMENT OF THE PROBLEM (PROBLEM FORMULATION)

A baseline RC structure (4-story internal RC special moment frame structure) as used in the FEMA P695 [14], was selected for this study. This structure was redesigned by the PBPD approach as introduced in reference [1]. The baseline structure and the PBPD structure were subjected to extensive inelastic pushover analysis, then tested with soil half-space (elastic support) to provide a simplified soil-structure-interaction model. The frames are used to support both vertical and horizontal loads.

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).
- Design base shear = 858.5 kN (193 kip), and (V/W) = 0.092.
- Three bays typical four stories with bay width = 9.14m (30 feet).
- First story/Upper stories height are 4.57/3.96 m (15/13 feet).

2.2. Material Properties

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

2.3. Soil Properties

Two main types of soils are used for soil structure interaction, these two types are listed in Table 1 with three subtypes for each.

Table 1: Properties of soil.

Soil Type	Subtypes	Dry Density (kN/m^3)	Poisson's Ratio	Young's Modulus (N/mm^2)	Shear Modulus (N/mm^2)
Clay	Soft	17.5	0.40	8	2.86
	Medium		0.35	22.5	8.33
	Stiff		0.30	65	25.00
Sand	Loose	14.5	0.25	15	6.00
	Medium		0.30	30	11.54
	Dense		0.35	60	22.22

3. MODEL DESCRIPTION

SAP2000 v20 software analysis package was used in this study to perform pushover analysis. Fourteen models were produced as described in Table 2. 2D-models were created for each case and the P-Delta effect was considered in all of them - Figure 2. The foundation soil is modeled by replacing the support by solid elements, extended to approximately five times building height in each direction, with relevant properties. The external joints of the solid elements (at the end sides of solid elements) were constrained against horizontal displacement, while the joints at the most bottom level were constrained against horizontal and vertical direction. For SSI models, strip footings were considered with section dimensions 0.90m x 1.50m (3.0ft x 5.0ft), and typical top and bottom reinforcement = 2000mm^2.

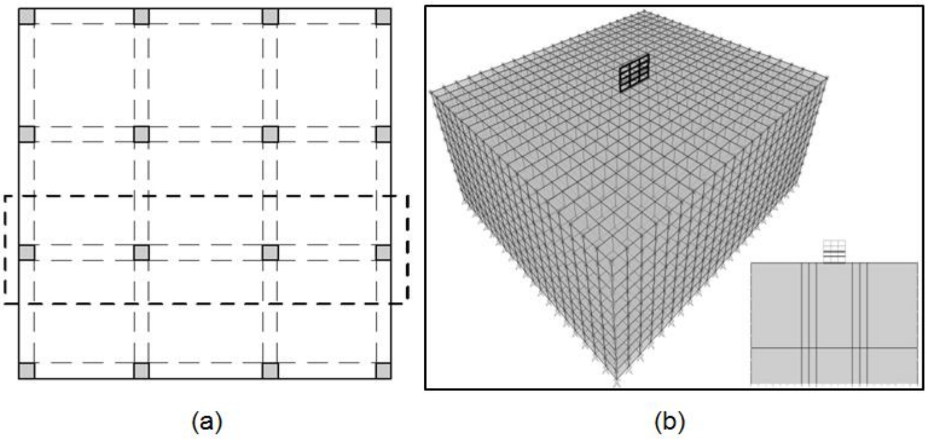


Figure 2: (a) Building Configuration. (b) SAP2000 2D-Model - With SSI.

Table 2: Analysis models produced.

Model Description	Design Following Code	Design Following PBPD
Without SSI	1 model	1 model
With SSI	6 models	6 models

4. RESULTS AND DISCUSSION

4.1. Fundamental Time Period

Fundamental time period values for fixed base and flexible base structures are listed in Table 3. Period lengthening calculations are based on Equation 1 and 2D-models output. Equation 1 assumed equivalent soil springs with stiffness calculated based on isolated footing design, and on a foundation level 1.50m below ground surface, with dimensions 4.00m x 4.00m x1.00m for external columns and 5.50m x 5.50m x 1.00m for internal columns. Finite element models provided higher values for the time period. This difference increased with the increase of soil flexibility.

Table 3: Fundamental time period values of structures.

Model Description	Support Type	Time Period (second) Design following code		Time Period (second) Design following PBPD	
		Equation 1	2D-Model	Equation 1	2D-Model
Without SSI	Fixed-base support	-	0.848	-	1.018
With SSI (considering period lengthening)	Soft Clay	2.599	4.689	3.120	4.689
	Medium Clay	1.719	2.803	2.063	2.441
	Stiff Clay	1.233	1.503	1.480	1.504
	Loose Sand	2.070	2.883	2.485	2.884
	Medium Sand	1.566	2.014	1.880	2.015
	Dense Sand	1.248	1.362	1.498	1.363

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 have a direct relationship with soil flexibility. Frames designed using PBPD were less affected by SSI.

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

Model Description	Support Type	Max. Inter-story Drift Design following code	Max. Inter-story Drift Design following PBPD	Max. roof displacement (m) Design following code	Max. roof displacement (m) Design following PBPD
Without SSI	Fixed-base support	1.16 %	1.02 %	0.145	0.142
With SSI	Soft Clay	2.15 %	1.55 %	0.253	0.222
	Medium Clay	1.86 %	1.41 %	0.208	0.201
	Stiff Clay	1.70 %	1.29 %	0.188	0.181
	Loose Sand	1.98 %	1.44 %	0.226	0.206
	Medium Sand	1.80 %	1.39 %	0.201	0.197
	Dense Sand	1.71 %	1.29 %	0.188	0.182

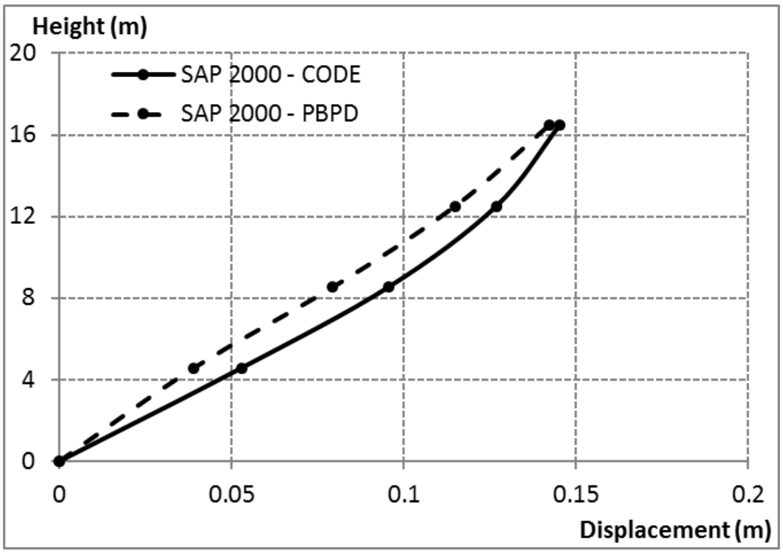


Figure 3: Floor Displacement - Without SSI - Fixed-base support.

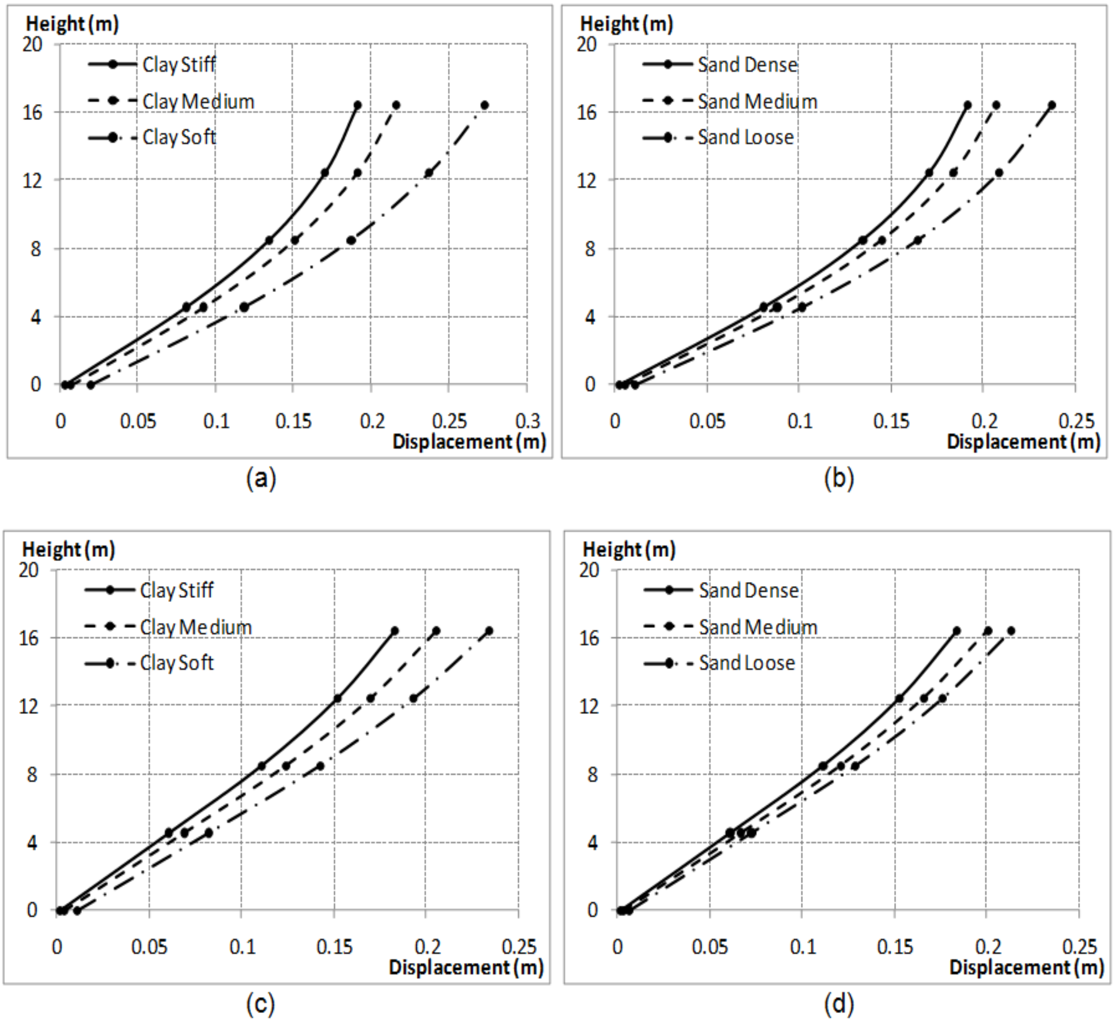


Figure 4: Floor Displacement for (a) Clay Soil - Design Following Code. (b) Sand Soil - Design Following Code. (c) Clay Soil - Design Following PBPD. (d) Sand Soil - Design Following PBPD.

4.3. Capacity and Base Shear

As per FEMA 356 [13], 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 design base shear following code was 858.5 kN (193 kips) while the design base shear using performance based plastic design was 1243.7 kN (279.6 kips) [1]. The P-Delta curves resulting from pushover analysis for all 14 models, modified to be base shear ratio (Base shear to building weight ratio – P/W) versus lateral drift ratio, are presented in Figures 5 and 6. Structure 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 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	Support Type	Capacity at 2% drift ratio (kN) Design following code	Capacity at 2% drift ratio (kN) Design following PBPD	Capacity at 3% drift ratio (kN) Design following code	Capacity at 3% drift ratio (kN) Design following PBPD
Without SSI	Fixed-base support	2315	1393	1933	1197
With SSI	Soft Clay	2227	1226	1982	883
	Medium Clay	2227	1226	---	863
	Stiff Clay	2227	1197	---	863
	Loose Sand	2217	1226	---	---
	Medium Sand	2227	1226	---	873
	Dense Sand	2227	1216	---	853

Table 6: Maximum capacity base shear of structures.

Model Description	Support Type	Max. base shear (kN) Design following code	Max. base shear (kN) Design following PBPD
Without SSI	Fixed-base support	2600	1530
With SSI	Soft Clay	2276	1334
	Medium Clay	2364	1364
	Stiff Clay	2384	1364
	Loose Sand	2335	1354
	Medium Sand	2374	1364
	Dense Sand	2384	1364

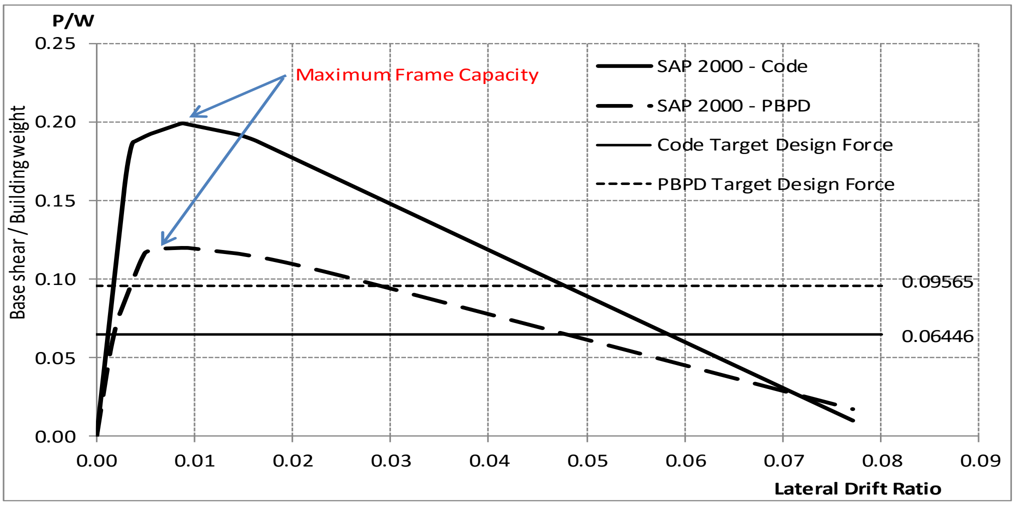
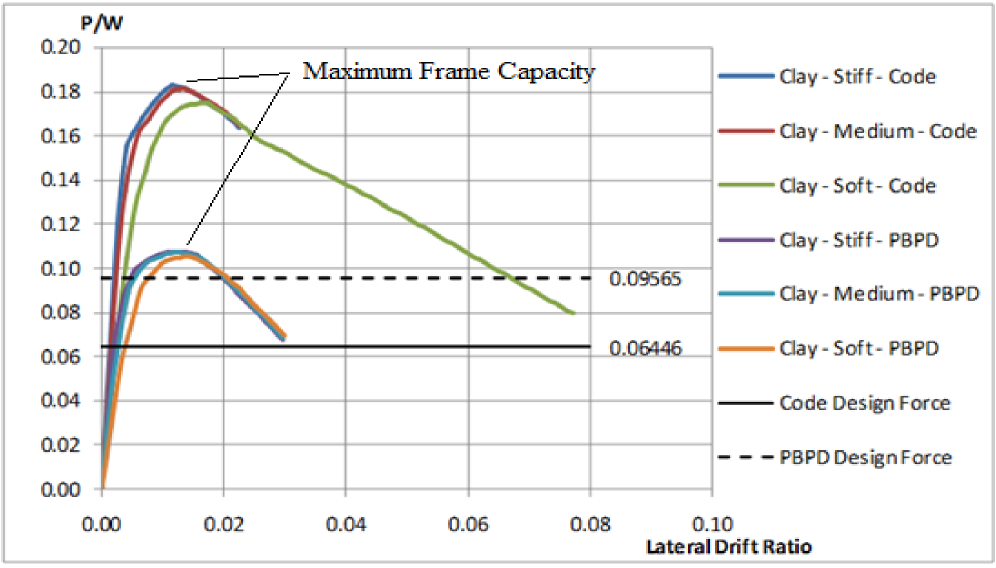
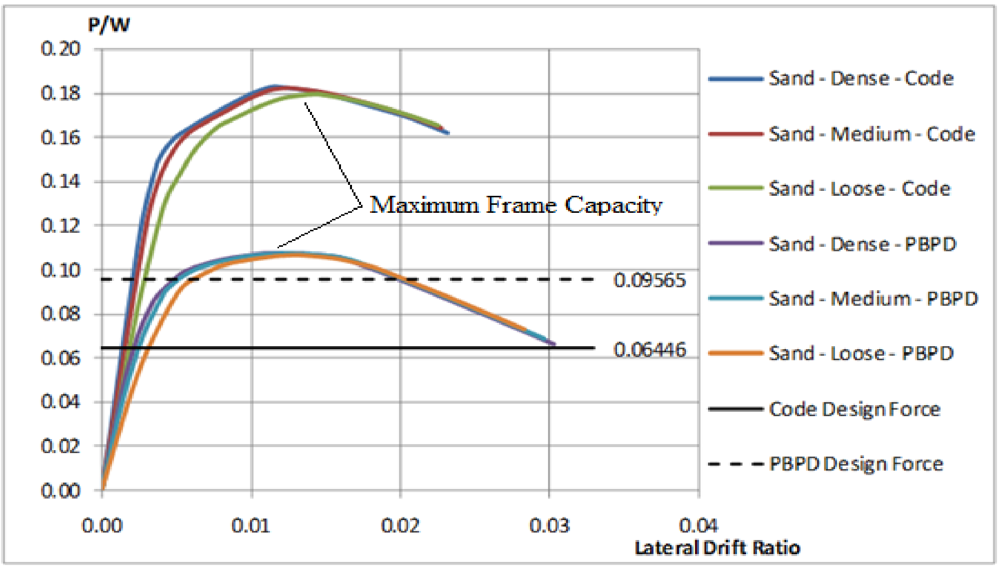


Figure 5: Base shear ratio versus Lateral drift ratio for fixed base support.



(a)



(b)

Figure 6: Base shear ratio versus Lateral drift ratio. (a) Clay soil. (b) Sand soil.

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. SSI can change the behavior of the fixed base structure.

This paper presents an assessment of original code design and PBPD methods to design RC SMF systems considering soil-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 depending on the flexibility of soil.
b. Time period is increasing with the increase in soil flexibility.
c. Using PBPD method lead to an increase in time period.
d. Time period calculated using finite element models is higher than that calculated using equivalent soil springs with stiffness calculated using Equation 1, specially with increasing soil flexibility.

5.2. Drift and Displacement

a. Using PBPD method decreases inter-story drift ratio.
b. Considering SSI increases inter-story drift and roof displacement for both design methods, however PBPD causes a less increase in both values.
c. Inter-story drift and roof displacement values increase with increasing soil flexibility.

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 less than that of code elastic design.
c. Considering SSI reduces the capacity of frames designed following code elastic design and PBPD.
d. Capacity increases with the increase in soil stiffness.
e. At 2% “Life Safety” drift limit, the capacity of frames designed using both methods were higher than the acceptable design target capacity.
f. Frame with fixed support and designed following code elastic design and PBPD, can keep capacity which exceeds the design base shear until reaching the 3% “Collapse Prevention” drift limit.
g. For models with flexible support, at 3% drift limit, frames designed following code elastic design method failed in reaching the “Collapse Prevention” performance level, while frames designed by PBPD reached the 3% drift limit, but they could not exceed it and their capacities did not exceed the target design base shear.

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