Seismic Behavior of High-Strength Reinforced Concrete Building Frames and Dual Systems Considering Soil Structure Interaction

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Abstract -- This paper investigates the seismic behavior of moment resisting building frames and dual systems constructed from Normal-Strength Concrete (NSC with fc' = 25 MPa) and High-Strength Concrete (HSC with fc' = 75 MPa) considering Soil Structure Interaction (SSI) using Wolf model, Gazetas model, the method used by the International Building Code (IBC-2012) and the method used by the Egyptian code for soil mechanics and foundation design (ECP 202-2007). The study also includes the effect of soil type and the level of foundation. El Centro earthquake record has been selected as the input ground motion. The selected structures had been analyzed with aid of the computer program OPNSEES and material nonlinearity had been accounted for. The HSC models were designed with allowance for two options; keeping the dimensions of the cross sections constant or reduced along the height. The results showed that the calculated seismic response of multi-story reinforced concrete building frames and dual systems considering SSI is sensitive to the variation in the concrete strength. Considering the SSI using Wolf model for the case of soft soil with 12-story building frame resulted in an increase in the roof displacement relative to the fixed base by 18.0%, 16.0% and 15.0% for NSC, HSC with reduced sections and HSC with constant sections, respectively, while for Gazetas model these ratios are 20.0%, 21.0% and 12.0%, respectively, and for the IBC-2012 model these ratios are 13.0%, 15.0%, and 9.0%, respectively. For 12-story dual systems, considering the SSI according to Wolf model with soft soil resulted in an increase in the roof displacement relative to the case of fixed base by 40%, 38%, and 9% for NSC and HSC (reduced sections) and HSC (constant sections), respectively, while for Gazetas model these ratios are 63%, 61.0% and 14%, respectively, and for the IBC-2012 model these ratios are 42%, 30.0%, and 23.0%, respectively. The calculated maximum story drift considering the SSI with soft soil S1 for 12-story building frame constructed from HSC with fc' = 75 MPa exceeds the story drift limit required by the international codes by 7%, 13% and 67% for Wolf, Gazetas and ECP model, respectively. For the 12-story dual system the calculated maximum story drift is still within the limit of the international codes due to the large stiffness of the shear walls.

Index Terms - soil structure interaction, seismic response, high strength concrete, dual systems, Wolf and Gazetas model

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1 INTRODUCTION

Many researchers studied the effect of Soil Structure Interaction (SSI) on the seismic behavior of reinforced concrete multistory building frames and dual systems constructed from Normal-Strength Concrete (NSC) [1, 2, and 3]. With the commercial availability of High-Strength Concrete (HSC) with compressive strength approaching 140 MPa, it has become necessary to study the seismic behavior of HSC building frames and dual systems considering the SSI.

When using HSC in the construction of building frames and dual systems the cross sections of columns and shear walls will be reduced. The reduction in cross sections will then affect the seismic response although the concrete strength has increased. In this regard, models for considering the SSI have been proposed by many researchers; e.g., Gazetas model [4] and Wolf model [5]. In addition, many international codes includes provisions for the SSI; e.g., the International Building Code (IBC-2012) [6] and the Egyptian code for soil mechanics and foundation design (ECP 202-2007) [7].

The main objective of this paper is to study the seismic behavior of multi-story building frames and dual systems constructed from NSC with fc'=25 and HSC with fc'=75 MPa considering the SSI. Moreover, the effect of different models for considering the SSI on the seismic response of two structural systems will be evaluated.

2 MODELS OF SOIL STRUCTURE INTERACTION

2.1 Gazetas Model

This model provides a complete set of algebraic formulas and dimensionless charts to compute the dynamic stiffness's and damping coefficients of foundation rested or embedded on a homogenous half space. For surface foundation the stiffness (K) and damping Coefficient (C) are expressed as follows [4]:

- **Vertical direction**

$$K_z = (2G\,L\,/\,1-\nu)(0.73+1.54\chi^{0.75})$$
(1)

$$C_z = \gamma V_{La} A_b + (2K_z * \beta / \omega)$$
(2)

- **Horizontal direction**

$$K_H = K_y - G\,L(0.2/0.75-\nu)(1-B/L)$$
(3)

$$K_y = (2G\,L\,/\,2-\nu)(2+2.5\chi^{0.85})$$
(4)

$$C_H = \gamma V_s A_b + (2K_H * \beta / \omega)$$

(5)

- **Rocking direction**

$$K_r = (3G / 1 - \nu)\, I_{by}^{0.75}\, (L / B)^{0.15}$$

(6)

$$C_r = \gamma V_{La}\, I_{by} + (2\, K_r * \beta / \omega)$$

(7)

For embedded foundation the stiffness (K) and damping coefficient (C) are expressed as follow:

- **Vertical direction**

$$K_{z\ emb.} = K_z \left[1+(1/21)(D/B)(1+1.3\chi)\right]\left[1+0.2(A_w / A_b)^{0.67}\right] \quad (8)$$

$$C_{z\,emb.} = C_z + \gamma V_S A_W + (2K_{z\,emb.} * \beta / \omega)$$

(9)

- **Horizontal direction**

$$K_{H\,emb.} = K_H * K_{y\,emb.} / K_y$$

(10)

$$K_{y\,emb.} = K_y \left[1 + 0.15(D / B)^{0.5}\right] * \left[1 + 0.52(h / B)(A_w / L^2)^{0.4}\right] \quad (11)$$

$$C_{H\,emb.} = C_H + 4\gamma V_{La} Bd + 4\gamma V_S Ld + (2K_{H\,emb.} * \beta / \omega) \quad (12)$$

- **Rocking direction**

$$K_{remb.} = K_r \left[1 + 0.92(d / L)^{0.6} * \left(1.5 + (d / L)^{1.9} (d / L)^{-0.6}\right)\right]$$

(13)

$$C_{remb.} = C_r + \gamma I_{by}\, (d / L) *$$
$$\left[V_{La}(d^2 / L^2) + 3V_S + V_S \left(1 + d^2 / L^2\right)\right].\eta_r + \left(2K_{remb.} * \beta / \omega\right)$$

(14)

2.2 Wolf Model

In this model, the rigid base-mat is modeled with a truncated semi-infinite cone of equivalent radius r0, apex height zo for various degrees of freedom with corresponding aspect ratio (zo/ro), which depends on the soil and foundation properties. For surface foundation the stiffness (K) and damping coefficient (C) are expressed as follows [5]:

- **Vertical direction**

$$K_z = (4G\, r_o / 1 - \nu)$$

(15)

$$C_z = \rho\ 2V_S\ A$$

(16)

Added mass $= 2.4\,(\nu - 1/3)\,.\rho.A.r_o$

(17)

- **Horizontal direction**

$$K_H = (8G\, r_o / 2 - \nu)$$

(18)

$$C_H = \rho V_S\ A$$

(19)

- **Rocking direction**

$$K_r = 8G\ r_o^3 \Big/ 3(1 - \nu)$$

(20)

$$C_r = \rho\ 2V_S\ I_r$$

(21)

Added mass $= 1.2\,(\nu - 1/3)\,.\rho.I_r\,.r_o$

(22)

For embedded foundation the stiffness (K) and damping coefficient (C) are expressed as follow:

- **Vertical direction**

$$K_{z\,emb.} = (4G\, r_o / 1 - \nu)(1 + 0.54\,e / r_o)(1 + 0.85 - 0.28\,e / r_o) \quad (23)$$

$$C_z = \rho\ 2V_S\ A$$

(24)

Added mass $= 2.4\,(\nu - 1/3)\,.\rho.A.r_o$

(25)

- **Horizontal direction**

$$K_H = (8G\, r_o / 2 - \nu)\,(1 + e / r_o)$$

(26)

$$C_H = \rho V_S\ A$$

(27)

- **Rocking direction**

$$K_r = (8G\ r_o^3 \Big/ 3(1 - \nu))\,(1 + 2.3\,e / r_o + 0.58\,(e / r_o)^3) \quad (28)$$

$$C_r = \rho\ 2V_S\ I_r$$

(29)

Added mass $= 1.2\,(\nu - 1/3)\,.\rho.I_r\,.r_o$

(30)

3 Seismic Codes Provisions for Considering SSI

3.1 IBC-2012 and ASCE-2010

The provisions of the IBC-2012 [6] for considering the SSI in the analysis of structures are similar to that of the ASCE7-2010 [8]. These codes require the following equations to be used when the soil structure interaction is to be considered:

- **Base shear**

$$\overline{V} = V - \Delta V$$

(31)

$$V = C_s * W$$

(32)

$$\Delta V = (Cs - \bar{C}s\ (0.05 / \bar{\beta}))\ W$$

(33)

- **Effective building period**

$$\bar{T} = T \sqrt{1 + \frac{\bar{K}}{K_H}\left(1 + \frac{K_H\ \bar{h}^2}{K_r}\right)}$$

(34)

$$\bar{K} = 4\pi^2\ (\bar{W} / g\,T^{\,2})$$

(35)

- **Lateral displacement**

$$\bar{\delta}_x = \frac{\bar{V}}{V}\left(\frac{M_o * h_x}{K_r} + \delta_x\right)$$

(36)

- **Effective damping**

$$\bar{\beta} = \beta_o * 0.05 / (\bar{T} / T)^3 \qquad (37)$$

3.2 ECP 202-2007

The Egyptian code for soil mechanics and foundation design gives a complete set of equations that can completely represent the soil flexibility such as the spring stiffness and damping coefficients for cases of surface and embedded foundations. For surface foundation the spring stiffness (K) and damping coefficient (C) are expressed as follows [7]:

- **Vertical direction**

$$Kz = 4G\,r_o / 1 - \nu$$

(38)

$$C_z = (3.4\,r_o^2 / 1 - \nu)\sqrt{\rho G}$$

(39)

- **Horizontal direction**

$$K_H = \frac{32\,(1-\nu)\,G\,r_o}{7 - 8\nu}$$

(40)

$$C_H = 18.4\,r_o^2\ (1 - \nu / 7 - 8\nu)\sqrt{\rho G}$$

(41)

- **Rocking direction**

$$K_r = 8G\,r_o^3 / 3\,(1 - \nu)$$

(42)

$$C_r = \frac{0.8\,r_0^4}{(1-\nu)\,(1+\beta_\varphi)}\sqrt{\rho G}$$

(43)

$$\beta_\varphi = \frac{3\,(1-\nu)}{8}\,(I_r / \rho\,r_o^5)$$

(44)

For embedded foundation the spring stiffness (K) and damping coefficient (C) are expressed as follow:

- **Vertical direction**

$$K_{z\ emb.} = K_z * \eta_z$$

(45)

$$\eta_z = 1 + 0.6\,(1 - \nu)\,(e / r_o)$$

(46)

$$C_{z\ emb.} = C_z * \left[1 + 1.9\,(1 - \nu)\,(e / r_o)\right] / \sqrt{\eta_z}$$

(47)

- **Horizontal direction**

$$K_{H\ emb.} = K_H * \eta_H$$

(48)

$$\eta_H = 1 + 0.55\,(2 - \nu)\,(e / r_o)$$

(49)

$$C_{H\ emb.} = C_H * \left[1 + 1.9\,(2 - \nu)\,(e / r_o)\right] / \sqrt{\eta_H}$$

(50)

- **Rocking direction**

$$K_{r\ emb.} = K_r * \eta_r$$

(51)

$$\eta_r = 1 + 1.2\,(1 - \nu)\,(e / r_o) + 0.2\,(2 - \nu)\,(e / r_o)^3 \qquad (52)$$

$$C_{r\ emb.} = C_r * \left[1 + 0.7\,(1 - \nu)\,(e / r_o) + 0.6\,(2 - \nu)\,(e / r_o)^3\right] / \sqrt{\eta_r} \qquad (53)$$

4 NONLINEAR ANALYSIS

4.1 Analytical Modelling

The seismic analysis in this study is performed using OPENSEES computer program [9]. The structures considered are two-dimensional moment-resisting building frames and dual systems. Columns and beams are modelled using force beam column element while zero length element is used to represent spring stiffness's and damping coefficient in the vertical, horizontal, and rocking direction to take the SSI into consideration as shown in Fig. 1.

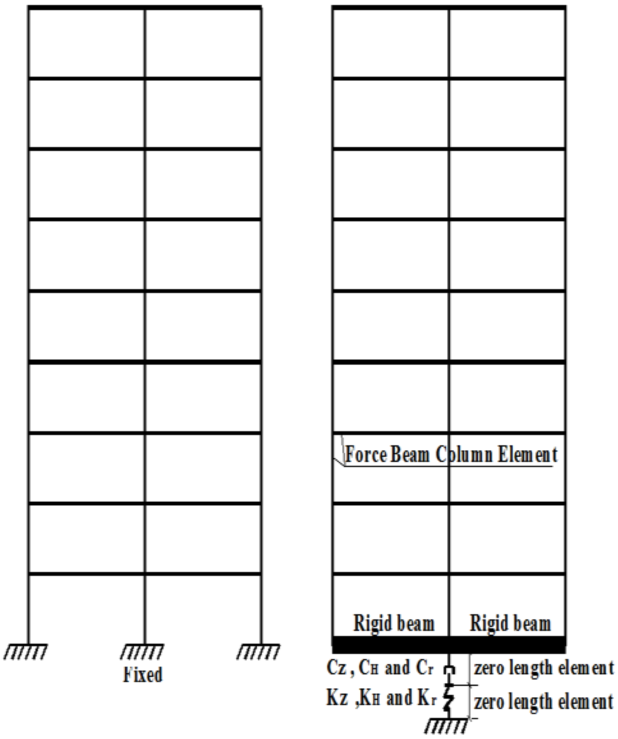


Fig. 1 Soil Structure Interaction Modelling.

4.2 Adopted Material Models and Properties

For NSC (with design cylinder compressive strength fc' = 25 MPa) and for HSC (fc'=75 MPa) in compression, Concrete 04 material in opensees library is used to model concrete behavior in both compression and tension. There are six values required to define concrete 04 material in the OPENSEES program as shown in Fig. 2. For concrete in compression the model suggested by Daniel and Patrick [10] was used. The modulus of elasticity for NSC and HSC is calculated using the equations recommended by the ACI 318-2014 [11]. For concrete in tension the model suggested by massicotte et. al. [12] has been used. For the steel reinforcement, Steel 01 in the program material library has been used, Fig. 3.

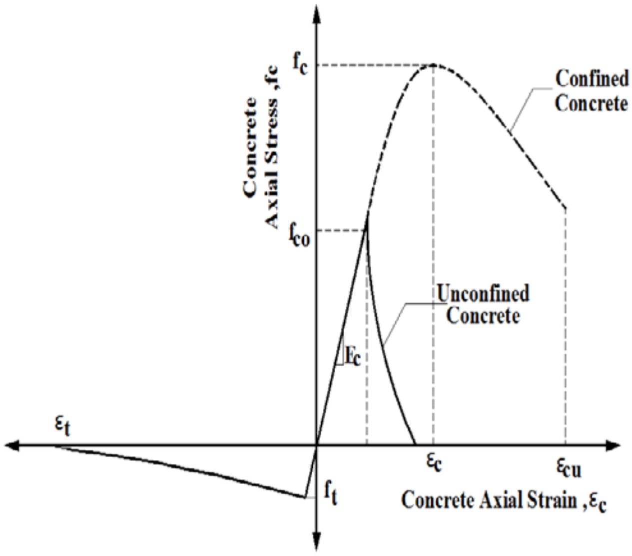


Fig. 2 Adopted Model of Concrete.

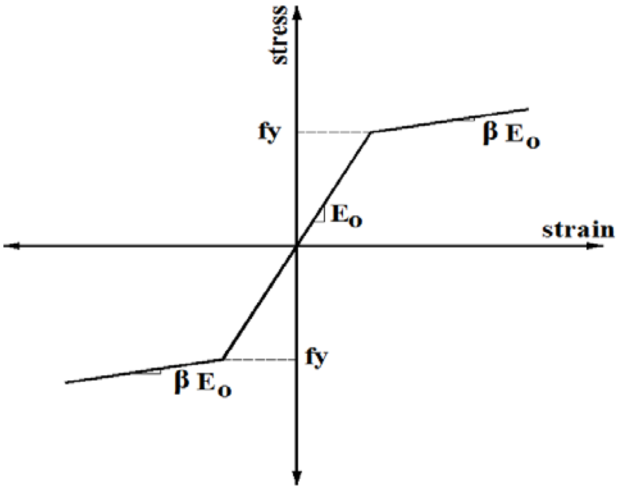


Fig. 3 Adopted Model of Steel.

5 THE INVESTIGATED PARAMETERS

5.1 Strength of Concrete

The selected studied examples are constructed from NSC with fc' =25 MPa and with HSC with fc' =75 MPa. For high strength concrete building frames and dual systems, two cases of sections dimensions have been studied. The first case is HSC building frames and dual systems with reduced section dimensions as the concrete strength increased (here will be referred to as reduced sections) and the second case is HSC frames and dual systems with constant section dimensions as in the case of NSC (here will be referred to as constant sections).

5.2 Soil Types and Properties

Three different types of soils have been selected with their shear modulus, shear wave velocity, poisons ratio and unit weight given in Table 1. Soil (S1) is a soft soil with shear wave velocity equal to 60 m/sec while soil (S2) is a medium soil with shear wave velocity equal to 120 m/sec. Both of soil (S1) and soil (S2) can be classified as soil subclass (D) in accordance with the Egyptian code of loads (ECP 201-2012). Soil (S3) is a stiff soil with shear wave velocity equal to 360 m/sec and can be classified as soil subclass (B) in accordance with the Egyptian code of loads (ECP 201-2012) [13,14].

TABLE 1: Properties of the Studied Soil Types.

Soil model	Soil type	Shear wave velocity VS (m/sec.)	Shear modulus G (N/mm2)	Unit weight γ (t/m3)	Poisons ratio μ
S1	soft soil	60	5.8	1.6	0.4
S2	Medium soil	120	26	1.8	0.4
S3	Stiff soil	360	264	2	0.35

5.3 Foundation Cases

Two foundation cases have been considered in this study, (Surface) and (Embedded) foundations. Embedded foundation represent the case where basement is used while surface foundation can be considered where no basement is used. The embedded height measured from the ground surface to the level of foundation is taken equal to 3.3 m for all embedded foundation cases.

5.4 Studied Models for the SSI

For considering the SSI, the model proposed by Gazetas [4] and also the model proposed by Wolf [5] are utilized. In addition, the method of considering SSI proposed by the IBC-2012 and the method proposed by the ECP 202-2007 will be employed.

6 SELECTION OF EARTHQUAKE GROUND MOTION

In this dynamic analysis, the Imperial Valley North-South component of the 1940 El Centro (with peak ground acceleration PGA =0.34g) is adopted as shown in Fig. 4. This record has been selected in order to match the "highest design level" earthquake in the United States (IBC-2012) and Europe (Regions of ductility Class "High" required by EC-8 [15]).

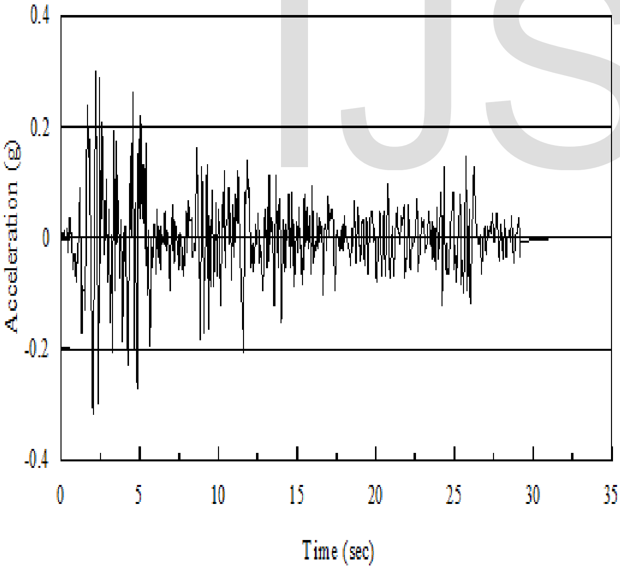
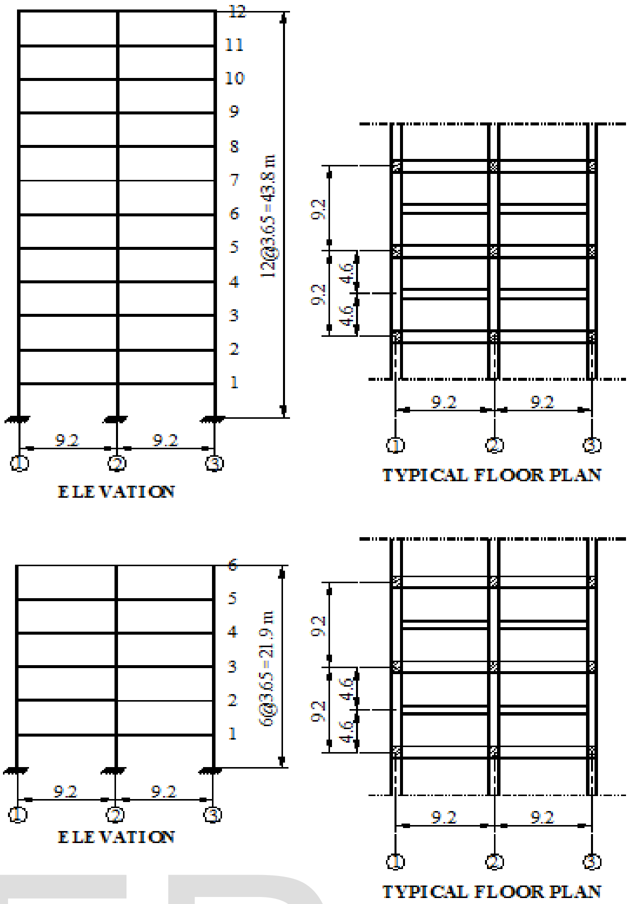


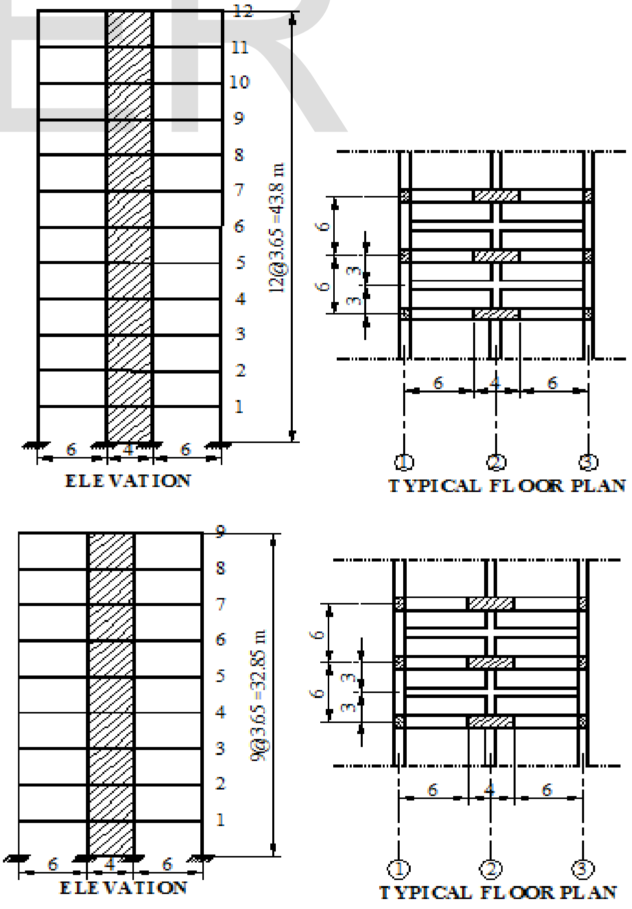
FIG. 4 El Centro Earthquake Record.

7 CONFIGURATION OF THE STUDIED BUILDING FRAMES AND DUAL SYSTEMS

Two multi-story reinforced concrete moment resisting building frames and other two dual systems, have been analyzed using OPENSEES program. The analyzed frames have 12 and 6 stories [16] while the analyzed dual systems have 12 and 9 stories [17] as shown in Fig. 5.



(a) Configuration of 12 and 6 Stories Building Frames



(b) Configuration of 12 and 9 Stories Dual Systems

Fig. 5 Configuration of the Study Systems

8 SEISMIC BEHAVIOR OF THE SELECTED STRUCTURAL MODELS.

8.1 Concrete Compressive Strength and the Fundamental Period of Vibration

The results showed that, for all the four models and for the three types of soils considered in this study, the calculated period of vibration increases when considering the SSI compared with the case of fixed base.

As shown in Table 2, considering the SSI using Wolf model for the case of soft soil with 12-story building frames resulted in an increase in the period by 13%, 13%, and 18% for NSC and HSC (reduced sections) and HSC (constant sections), respectively, while for Gazetas model these ratios are 21%, 22% and 29%, respectively and for the IBC-2012 model these ratios are 12%, 12%, and 17%, respectively. For the 12-story dual systems, Table 3 shows that considering the SSI using Wolf model with soft soil results in an increase in the period by 28%, 29.9%, and 39.2% for NSC and HSC (reduced sections) and HSC (constant sections), respectively, while for Gazetas model these ratios are 45.1%, 47.9% and 61.8% respectively and for the IBC-2012 model these ratios are 47%, 42%, and 61.4%, respectively. Table 2 shows also that the results for the period of vibration considering the SSI using, ECP 202-2007 model are approximately similar to that of Wolf model. In general the increase in the period of vibration when considering the SSI for 12-story dual system is relatively more than that of 12-story building frame for HSC and NSC. Considering the SSI using the four studied models for the case of 12-story moment resisting frame and dual system with fc' = 75 MPa (reduced sections) the period of vibration increases with approximately the same ratios as for the case of NSC with fc' = 25 MPa.

8.2 Concrete Compressive Strength and the Base Shear

The comparison between the base shear for the 12-story building frame and the dual system considering the SSI is given in Tables 4 and 5 and also is shown in Figs. 6 and 7. The results show that, for all the four models and for the three types of soils considered in this study, the calculated base shear decreases when considering the SSI compared with the case of fixed base.

As shown in Table 4, considering the SSI using Wolf model for the case of soft soil with the 12-story building frames decreases the base shear by 27%, 20%, and 11% for NSC and HSC (reduced sections) and HSC (constant sections), respectively, while for Gazetas model these ratios are 30%, 26% and 15%, respectively and for the IBC-2012 model these ratios are 15%, 13%, and 13%, respectively. For the 12-story dual systems, Table 5 shows that considering the SSI with soft soil decreases the base shear by 13.8%, 24.4% and 24.8% for NSC and HSC (reduced sections), and HSC (constant sections), respectively while for Gazetas model these ratios are 23.6%, 29.3% and 25.8% respectively, and for the IBC-2012 model these ratios are 10%, 18% and 18.7%, respectively.

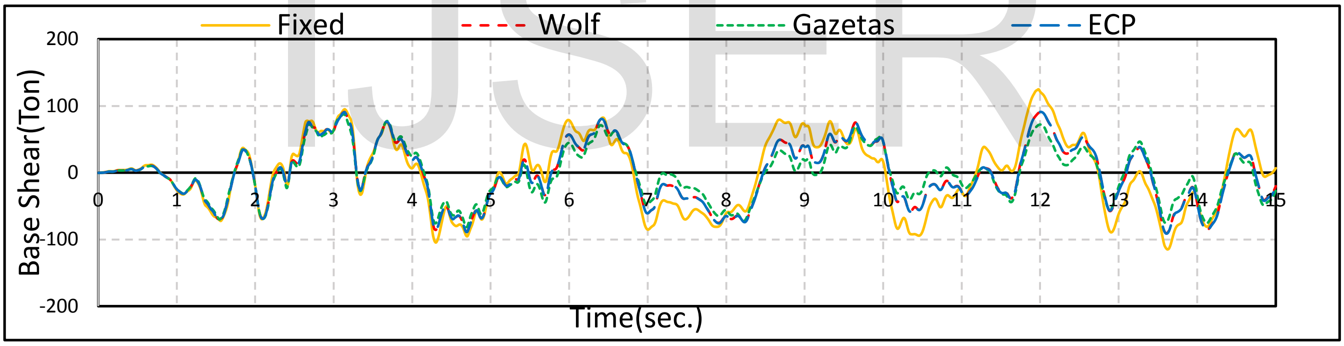


Fig. 6 Effect of the SSI on Base Shear for 12-Storries Moment-Resisting Frame Constructed from NSC with Surface Foundation Rested on Soft Soil (S1).

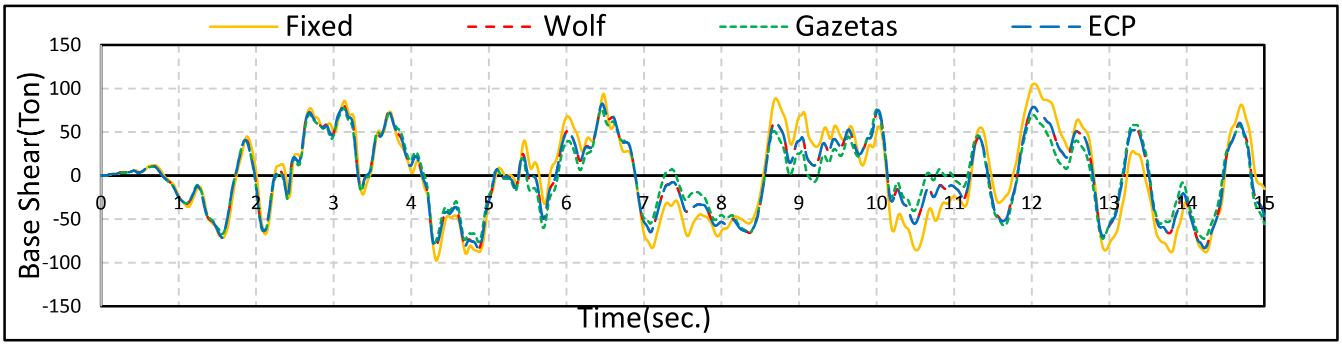


Fig. 7 Effect of the SSI on Base Shear for 12-Story Moment-Resisting Frame Constructed from HSC (Reduced Sections) with Surface Foundation Rested on Soft Soil (S1).

8.3 Concrete Compressive Strength and Roof Displacement

The effect of increasing the concrete strength from fc' = 25 MPa to fc' = 75 MPa on the seismic behavior of the models considering the SSI is shown in Tables 6 and 7 and Figs. 8 and 9. The results indicate that, for all four models and for the three types of soils considered in this study, the calculated roof displacement increases when considering the SSI compared with the case of fixed base.

As shown in Table 6, considering the SSI using Wolf model for the case of soft soil with 12-story building frames resulted in an increase in the roof displacement by 18%, 16% and 15% for NSC and HSC (reduced sections) and HSC (constant sections), respectively, while for Gazetas model these ratios are 20%, 21% and 12%, respectively and for the IBC-2012 model these ratios are 13%, 15%, and 9%, respectively. For the 12-story dual systems, Table 7 shows that considering the SSI using Wolf model with soft soil results in an increase in the roof displacement by 39.8%, 38.4%, and 9.3% for NSC and HSC (reduced sections) and HSC (constant sections), respectively, while for Gazetas model these ratios are 63.2%, 61% and 13.8%, respectively and for the IBC-2012 model these ratios are 41.5%, 30%, and 23%, respectively. In general, the relative increase in the roof displacement when considering the SSI for the 12-story dual system is relatively more than that of the 12-story building frames for HSC and NSC. The consideration of the SSI with the four studied models in the case of stiff soil (S3) results in very small increase in the roof displacement for surface and embedded foundations. In addition, the roof displacement for surface foundation is generally more than that of the embedded foundation for all the studied models with different types of soils and different concrete compressive strengths.

8.4 Story Drift

The calculated allowable values of story drift for the 12-story moment resisting building frame and 12-story dual system required by the IBC-2012, ECP 201-2012, and Euro code 8 (EC-8) for the highest design level are given in Tables 8 and 9.

For the 12-story building frame, considering the SSI using Wolf model with soft soil increases the drift by 19.25%, 28.1%, and 18.4% for NSC and HSC (reduced sections) and HSC (constant sections), respectively, while for Gazetas model these ratios are 25.7%, 34.9%, and 21%, respectively. For the 12-story dual system, Table 9 shows that considering the SSI using Wolf model with soft soil results in an increase in the drift by 40.5%, 25.2%, and 31% for NSC and HSC (reduced sections) and HSC (constant sections), respectively, while for Gazetas model these ratios are 45.6%, 29.5%, and 35.2%, respectively. The results indicates that, for the 12-story building frame constructed from HSC with reduced sections the calculated maximum story drift considering the SSI model exceeds the story drift limit required by the international codes by 7.4%, 13.2% and 6.5% for Wolf, Gazetas, and ECP model, respectively. For the 12-story dual system the calculated value of maximum story drift for NSC, HSC (reduced sections) and HSC (constant sections) considering the SSI using the four models and for all types of soils are still within the limit of the international codes due to the large stiffness of the shear walls.

TABLE 2: Comparison between Fundamental Periods of Vibration for 12-Story Building Frame Considering the SSI

Type of foundation	Soil type	Fundamental period(sec.)					Ratio of periods				% Variation in period			
		Fixed	Wolf	Gazetas	ECP 202-2007	IBC 2012	$\frac{T_W}{T_F}$	$\frac{T_G}{T_F}$	$\frac{T_{ECP}}{T_F}$	$\frac{T_{IBC}}{T_F}$	Wolf	Gazetas	ECP	IBC
		T_F	T_W	T_G	T_{ECP}	T_{IBC}								
NSC with f_c' = 25 MPa														
Surface	S_1	2.277	2.570	2.763	2.569	2.55	1.13	1.21	1.13	1.12	13%	21%	13%	12%
	S_2	2.277	2.417	2.518	2.417	2.408	1.06	1.11	1.06	1.06	6%	11%	6%	6%
	S_3	2.277	2.303	2.301	2.303	2.302	1.01	1.01	1.01	1.01	1%	1%	1%	1%
Embedded	S_1	2.277	2.460	2.457	2.516	2.447	1.08	1.08	1.1	1.07	8%	8%	10%	7%
	S_2	2.277	2.353	2.353	2.385	2.414	1.03	1.03	1.05	1.06	3%	3%	5%	6%
	S_3	2.277	2.290	2.289	2.296	2.289	1.01	1.01	1.01	1.01	1%	1%	1%	1%
HSC with f_c' = 75 MPa (Reduced Sections)														
Surface	S_1	2.221	2.520	2.717	2.519	2.5	1.13	1.22	1.13	1.12	13%	22%	13%	12%
	S_2	2.221	2.364	2.467	2.364	2.355	1.06	1.11	1.06	1.06	6%	11%	6%	6%
	S_3	2.221	2.248	2.245	2.248	2.246	1.01	1.01	1.01	1.01	1%	1%	1%	1%
Embedded	S_1	2.221	2.408	2.405	2.465	2.395	1.08	1.08	1.11	1.08	8%	8%	11%	8%
	S_2	2.221	2.299	2.299	2.332	2.36	1.04	1.04	1.05	1.06	4%	4%	5%	6%
	S_3	2.221	2.234	2.233	2.240	2.233	1.01	1.01	1.01	1.01	1%	1%	1%	1%
HSC with f_c' = 75 MPa (Constant Sections)														
Surface	S_1	1.889	2.235	2.454	2.233	2.211	1.18	1.29	1.18	1.17	18%	29%	18%	17%
	S_2	1.889	2.057	2.174	2.056	2.045	1.09	1.15	1.09	1.08	9%	15%	9%	8%
	S_3	1.889	1.921	1.904	1.921	1.92	1.02	1.01	1.02	1.02	2%	1%	2%	2%
Embedded	S_1	1.889	2.107	2.104	2.172	2.10	1.11	1.11	1.15	1.11	11%	11%	15%	11%
	S_2	1.889	1.981	1.981	2.018	2.052	1.05	1.05	1.07	1.08	5%	5%	7%	8%
	S_3	1.889	1.905	1.904	1.912	1.904	1.01	1.01	1.01	1.01	1%	1%	1%	1%

Table 3: Comparison between Fundamental Periods of Vibrations for 12-Story Dual System Considering the SSI

Type of foundation	Soil type	Fundamental period(sec.)					Ratio of periods				% Variation in period			
		Fixed	Wolf	Gazetas	ECP 202-2007	IBC 2012	$\frac{T_W}{T_F}$	$\frac{T_G}{T_F}$	$\frac{T_{ECP}}{T_F}$	$\frac{T_{IBC}}{T_F}$	Wolf	Gazetas	ECP	IBC
		T_F	T_W	T_G	T_{ECP}	T_{IBC}								
NSC with f_c '= 25 MPa														
Surface	S_1	1.570	2.011	2.279	2.009	2.309	1.280	1.451	1.279	1.47	28%	45.1%	27.9%	47%
	S_2	1.570	1.755	1.859	1.755	1.898	1.118	1.184	1.118	1.21	11.8%	18.4%	11.8%	21%
	S_3	1.570	1.604	1.597	1.604	1.632	1.022	1.017	1.022	1.04	2.2%	1.7%	2.2%	4%
Embedded	S_1	1.570	1.828	1.823	1.921	2.011	1.164	1.161	1.223	1.28	16.4%	16.1%	22.3%	28%
	S_2	1.570	1.665	1.661	1.709	1.740	1.060	1.058	1.088	1.11	6%	5.8%	8.8%	11%
	S_3	1.570	1.585	1.584	1.593	1.598	1.010	1.01	1.015	1.018	1%	1%	1.5%	1.8%
HSC with f_c '= 75 MPa (reduced sections)														
Surface	S_1	1.513	1.966	2.239	1.964	2.143	1.299	1.479	1.298	1.42	29.9%	47.9%	29.8%	42%
	S_2	1.513	1.704	1.811	1.703	1.789	1.126	1.197	1.125	1.18	12.6%	19.7%	12.5%	18%
	S_3	1.513	1.547	1.547	1.547	1.564	1.022	1.022	1.022	1.03	2.2%	2.2%	2.2%	3%
Embedded	S_1	1.513	1.778	1.773	1.874	1.886	1.175	1.172	1.238	1.24	17.5%	17.2%	23.8%	24%
	S_2	1.513	1.611	1.607	1.656	1.656	1.065	1.062	1.094	1.09	6.5%	6.2%	9.4%	9%
	S_3	1.513	1.522	1.521	1.521	1.536	1.01	1.005	1.005	1.015	1%	0.5%	0.5%	1.5%
HSC with f_c '= 75 MPa (constant sections)														
Surface	S_1	1.2996	1.8088	2.1027	1.8067	2.098	1.392	1.618	1.39	1.614	39.2%	61.8%	39%	61.4%
	S_2	1.2996	1.5181	1.6378	1.5177	1.663	1.168	1.26	1.168	1.279	16.8%	26%	16.8%	27.9%
	S_3	1.2996	1.3396	1.3321	1.3394	1.37	1.031	1.025	1.031	1.054	3.1%	2.5%	3.1%	5.4%
Embedded	S_1	1.2996	1.6019	1.5958	1.7077	1.784	1.233	1.228	1.31	1.373	23.3%	22.8%	31%	37.3%
	S_2	1.2996	1.4123	1.5378	1.4639	1.490	1.087	1.18	1.126	1.146	8.7%	18%	12.6%	14.6%
	S_3	1.2996	1.3395	1.3161	1.3271	1.331	1.031	1.03	1.02	1.024	3.1%	3%	2%	2.4%

Table 4: Comparison between the Base Shear for 12-Story Building Frame Considering the SSI

Type of foundation	Soil type	Base shear(ton)					Ratio of base shear				% Variation in base shear			
		Fixed	Wolf	Gazetas	ECP 202-2007	IBC 2012	$\frac{V_W}{V_F}$	$\frac{V_G}{V_F}$	$\frac{V_{ECP}}{V_F}$	$\frac{V_{IBC}}{V_F}$	Wolf	Gazetas	ECP	IBC
		V_F	V_W	V_G	V_{ECP}	V_{IBC}								
NSC with f_c '= 25 MPa														
Surface	S_1	124.8	90.9	87.6	91.3	105.7	0.73	0.70	0.73	0.85	-27%	-30%	-27%	-15%
	S_2	124.8	111.6	100.9	111.6	114.3	0.89	0.81	0.89	0.92	-11%	-19%	-11%	-8%
	S_3	124.8	122.1	122.5	122.3	124.2	0.98	0.98	0.98	0.99	-2%	-2%	-2%	-1%
Embedded	S_1	124.8	105.2	102.8	97.4	108.9	0.84	0.82	0.78	0.87	-16%	-18%	-22%	-13%
	S_2	124.8	118.1	116.6	114.8	114.5	0.95	0.93	0.92	0.92	-5%	-7%	-8%	-8%
	S_3	124.8	123.7	123.7	122.9	124.2	0.99	0.99	0.98	0.99	-1%	-1%	-2%	-1%
HSC with f_c '= 75 MPa (reduced sections)														
Surface	S_1	105.4	84.3	77.7	83.8	92	0.8	0.74	0.8	0.87	-20%	-26%	-20%	-13%
	S_2	105.4	94	90.9	94	96.7	0.89	0.86	0.89	0.92	-11%	-14%	-11%	-8%
	S_3	105.4	102.6	102.7	103	105	0.97	0.97	0.98	1	-3%	-3%	-2%	0%
Embedded	S_1	105.4	89	88.1	86.1	92.1	0.84	0.84	0.82	0.87	-16%	-16%	-18%	-13%
	S_2	105.4	99.8	99.9	97.6	96.8	0.95	0.95	0.92	0.92	-5%	-5%	-8%	-8%
	S_3	105.4	104.2	103.8	104.1	105	0.99	0.98	0.99	1	-1%	-1%	-1%	0%
HSC with f_c '= 75 MPa (constant sections)														
Surface	S_1	151.4	135.7	128.1	133.6	131.4	0.89	0.85	0.88	0.87	-11%	-15%	-12%	-13%
	S_2	151.4	145.3	141.4	147.2	141.3	0.96	0.93	0.97	0.93	-4%	-7%	-2%	-7%
	S_3	151.4	147.2	148.3	149.2	150.8	0.97	0.98	0.98	0.99	-3%	-2%	-3%	-1%
Embedded	S_1	151.4	139.8	139.2	137.4	130.4	0.92	0.92	0.91	0.86	-8%	-8%	-9%	-14%
	S_2	151.4	145.1	145.5	144.2	141.6	0.96	0.96	0.95	0.94	-4%	-4%	-5%	-6%

	S_3	151.4	149.5	148.3	147.9	150.8	0.99	0.98	0.98	0.99	-1%	-2%	-2%	-1%

Table 5: Comparison between the Base Shear for 12-Story Dual System Considering the SSI

Type of foundation	Soil type	Base shear(ton)					Ratio of base shear				% Variation in base shear			
		Fixed	Wolf	Gazetas	ECP 202-2007	IBC 2012	$\frac{V_W}{V_F}$	$\frac{V_G}{V_F}$	$\frac{V_{ECP}}{V_F}$	$\frac{V_{IBC}}{V_F}$	Wolf	Gazetas	ECP	IBC
		V_F	V_W	V_G	V_{ECP}	V_{IBC}								
NSC with f_c' = 25 MPa														
Surface	S_1	159.1	137.1	121.6	138.3	142.3	0.862	0.764	0.869	0.894	-13.8%	-23.6%	-13%	-10%
	S_2	159.1	150.9	153.1	151.6	154.1	0.948	0.962	0.953	0.968	-5.2%	-3.8%	-4.7%	-3%
	S_3	159.1	158.9	158.3	158.9	159.0	0.998	0.995	0.999	0.999	-0.2%	-0.5%	-0.1%	-0.1%
Embedded	S_1	159.1	144.4	133.9	139.4	149.4	0.908	0.842	0.876	0.939	-9.2%	-15.8%	-12%	-6%
	S_2	159.1	156.5	150.1	151.4	155.6	0.984	0.943	0.952	0.978	-1.6%	-5.7%	-4.8%	-2%
	S_3	159.1	159.0	158.9	159.0	159.0	0.999	0.999	0.999	0.999	-0.1%	-0.1%	-0.1%	-0.1%
HSC with f_c' = 75 MPa (reduced sections)														
Surface	S_1	171.5	129.6	121.3	130.1	141.3	0.756	0.707	0.758	0.824	-24.4%	-29.3%	-24%	-18%
	S_2	171.5	166.2	164.8	168.3	167.4	0.969	0.961	0.981	0.976	-3.1%	-3.9%	-1.9%	-2.4%
	S_3	171.5	169.8	169.5	169.8	170.0	0.990	0.988	0.990	0.991	-1%	-1.2%	-1%	-0.9%
Embedded	S_1	171.5	147.5	147.3	146	154.3	0.860	0.859	0.851	0.899	-14%	-14.1%	-15%	-10%
	S_2	171.5	168.4	167.9	168.1	168.7	0.982	0.979	0.980	0.984	-1.8%	-2.1%	-2%	-1.6%
	S_3	171.5	171.2	171.3	171.2	170.1	0.998	0.999	0.998	0.992	-.2%	-0.1%	-0.2%	-0.8%
HSC with f_c' = 75 MPa (constant sections)														
Surface	S_1	181.35	136.35	134.5	139.4	147.45	0.752	0.742	0.768	0.813	-24.8%	-25.8%	-23.2%	-18%
	S_2	181.35	159.63	164.025	158.77	162.7	0.880	0.904	0.875	0.897	-12%	-9.6%	-12.5%	-10%
	S_3	181.35	179.175	178.6	177.37	176.12	0.988	0.985	0.978	0.971	-1.2%	-1.5%	-2.2%	-2.9%
Embedded	S_1	181.35	146.14	145.7	144.8	152.31	0.806	0.803	0.798	0.839	-19.4%	-19.7%	-20.2%	-16%
	S_2	181.35	161.25	164.025	155.35	168.4	0.889	0.904	0.856	0.928	-11.1%	-9.6%	-14.4%	-7.2%
	S_3	181.35	179.175	177.27	180.7	176.05	0.988	0.977	0.996	0.971	-1.2%	-2.3%	-0.4%	-2.9%

Table 6: Comparison between the Roof Displacements for 12-Story Building Frame Considering the SSI

Type of foundation	Soil type	Roof displacement (m)					Ratio of displacements				% Variation in displacement			
		Fixed	Wolf	Gazetas	ECP 202-2007	IBC 2012	$\frac{\delta_W}{\delta_F}$	$\frac{\delta_G}{\delta_F}$	$\frac{\delta_{ECP}}{\delta_F}$	$\frac{\delta_{IBC}}{\delta_F}$	Wolf	Gazetas	ECP	IBC
		δ_F	δ_W	δ_G	δ_{ECP}	δ_{IBC}								
NSC with f_c' = 25 MPa														
Surface	S_1	0.252	0.2968	0.3024	0.2990	0.2845	1.18	1.20	1.19	1.13	18%	20%	19%	13%
	S_2	0.252	0.264	0.269	0.264	0.254	1.05	1.07	1.05	1.01	5%	7%	5%	1%
	S_3	0.252	0.254	0.253	0.254	0.252	1.01	1.0	1.01	1	1%	0%	1%	0%
Embedded	S_1	0.252	0.2824	0.276	0.2824	0.269	1.12	1.10	1.12	1.07	12%	10%	12%	7%
	S_2	0.252	0.259	0.257	0.261	0.252	1.03	1.02	1.04	1	3%	2%	4%	0%
	S_3	0.252	0.253	0.253	0.253	0.251	1	1	1	1	1%	1%	0%	0%
HSC with f_c' = 75 MPa (reduced sections)														
Surface	S_1	0.261	0.3105	0.3151	0.3116	0.299	1.16	1.21	1.19	1.15	16%	21%	19%	15%
	S_2	0.261	0.269	0.276	0.272	0.256	1.03	1.06	1.04	0.98	3%	6%	4%	-2%
	S_3	0.261	0.265	0.262	0.264	0.262	1.02	1	1.01	1	2%	0%	1%	0%
Embedded	S_1	0.261	0.2948	0.2926	0.297	0.2817	1.13	1.12	1.14	1.08	13%	12%	14%	8%
	S_2	0.261	0.269	0.265	0.268	0.268	1.03	1.02	1.03	1.03	3%	2%	3%	3%
	S_3	0.261	0.264	0.264	0.263	0.26	1.01	1.01	1	1	1%	1%	0%	0%
HSC with f_c' = 75 MPa (constant sections)														
Surface	S_1	0.245	0.282	0.274	0.283	0.267	1.15	1.12	1.15	1.09	15%	12%	15%	9%
	S_2	0.245	0.269	0.263	0.256	0.26	1.10	1.07	1.04	1.06	10%	7%	4%	6%
	S_3	0.245	0.246	0.246	0.245	0.247	1.01	1.01	1	1.01	1%	1%	0%	1%
Embedded	S_1	0.245	0.279	0.272	0.272	0.264	1.14	1.11	1.11	1.08	14%	11%	11%	8%

	S_2	0.245	0.258	0.251	0.27	0.261	1.05	1.02	1.10	1.07	5%	2%	10%	7%
	S_3	0.245	0.245	0.245	0.245	0.245	1.0	1.0	1	1	0%	0%	0%	0%

Table 7: Comparison between roof Displacements for 12-Story Dual System Considering the SSI

Type of foundation	Soil type	Roof displacement (m)					Ratio of displacements				% Variation in displacement			
		Fixed δ_F	Wolf δ_W	Gazetas δ_G	ECP 202-2007 δ_{ECP}	IBC 2012 δ_{IBC}	$\frac{\delta_W}{\delta_F}$	$\frac{\delta_G}{\delta_F}$	$\frac{\delta_{ECP}}{\delta_F}$	$\frac{\delta_{IBC}}{\delta_F}$	Wolf	Gazetas	ECP	IBC
NSC with f_c' = 25 MPa														
Surface	S_1	0.171	0.239	0.279	0.245	0.242	1.398	1.632	1.433	1.415	39.8%	63.2%	43.3%	41.5%
	S_2	0.171	0.198	0.230	0.199	0.209	1.158	1.345	1.164	1.222	15.8%	34.5%	16.4%	22.2%
	S_3	0.171	0.172	0.173	0.172	0.176	1.006	1.012	1.006	1.030	0.6%	1.2%	0.6%	3%
Embedded	S_1	0.171	0.202	0.190	0.223	0.210	1.181	1.111	1.304	1.228	18.1%	11.1%	30.4%	22.8%
	S_2	0.171	0.180	0.172	0.185	0.185	1.053	1.006	1.082	1.082	5.3%	0.6%	8.2%	8.2%
	S_3	0.171	0.173	0.173	0.172	0.173	1.012	1.012	1.006	1.012	1.2%	1.2%	0.6%	1.2%
HSC with f_c' = 75 MPa (reduced sections)														
Surface	S_1	0.177	0.245	0.285	0.247	0.230	1.384	1.610	1.4	1.3	38.4%	61%	40%	30%
	S_2	0.177	0.205	0.233	0.208	0.214	1.153	1.316	1.175	1.210	15.3%	31.6%	17.5%	21%
	S_3	0.177	0.178	0.178	0.178	0.183	1.006	1.006	1.006	1.034	0.6%	0.6%	0.6%	3.4%
Embedded	S_1	0.177	0.209	0.204	0.226	0.206	1.181	1.153	1.277	1.164	18.1%	15.3%	27.7%	16.4%
	S_2	0.177	0.187	0.191	0.195	0.195	1.056	1.080	1.102	1.102	5.6%	5.6%	8%	10.2%
	S_3	0.177	0.177	0.177	0.177	0.179	1.0	1.0	1.0	1.011	0%	0%	0%	1.1%
HSC with f_c' = 75 MPa (constant sections)														
Surface	S_1	0.1582	0.173	0.180	0.172	0.1945	1.093	1.138	1.087	1.23	9.3%	13.8%	8.7%	23%
	S_2	0.1582	0.1672	0.1681	0.1702	0.183	1.06	1.062	1.076	1.16	6%	6.2%	7.6%	16%
	S_3	0.1582	0.164	0.163	0.164	0.1612	1.037	1.030	1.036	1.018	3.7%	3%	3.6%	1.8%
Embedded	S_1	0.1582	0.17	0.168	0.171	0.185	1.074	1.062	1.081	1.17	7.4%	6.2%	8.1%	17%
	S_2	0.1582	0.163	0.161	0.162	0.1676	1.03	1.017	1.024	1.06	3%	1.7%	2.4%	6%
	S_3	0.1582	0.161	0.16	0.161	0.16	1.017	1.011	1.017	1.011	1.7%	1.1%	1.7%	1.1%

Table 8: Comparison between the Story Drift for 12-Story Building Frame Considering the SSI and the Drift Limit Required by International Codes

Type of foundation	Soil type	Drift (m) Dynamic analysis considering SSI				Drift limit calculated by codes		
		Fixed	Wolf	Gazetas	ECP 202-2007	EC-8	ECP 201-2012	IBC 2012
		D_F	D_W	D_G	D_{ECP}			
NSC with f_c' = 25 MPa								
Surface	S_1	.0296	.0353	.0372	.0355	.0365	.0365	.365
	S_2	.0296	.0302	.0319	.0302			
	S_3	.0296	.030	.0301	.0301			
Embedded	S_1	.0296	.0322	.0323	.0329			
	S_2	.0296	.0299	.0291	.0301			
	S_3	.0296	.2984	.02985	.0297			
HSC with f_c' = 75 MPa (reduced sections)								
Surface	S_1	.0306	.0392	.0413	.0389	.0365	.0365	.0365
	S_2	.0306	.0314	.034	.0322			
	S_3	.0306	.0311	.036	.0311			
Embedded	S_1	.0306	.0349	.0342	.0361			
	S_2	.0306	.0312	.0307	.0325			
	S_3	.0306	.0306	.0306	.0311			
HSC with f_c' = 75 MPa (constant sections)								
Surface	S_1	.0271	.0321	.0328	.0322	.0365	.0365	.0365
	S_2	.0271	.0306	.0310	.0307			
	S_3	.0271	.0284	.0286	.0286			
Embedded	S_1	.0271	.0309	.0304	.0312			
	S_2	.0271	.0289	.0277	.0285			
	S_3	.0271	.0273	.0272	.0271			

Table 9: Comparison between the Story Drift for 12-Story Dual System Considering the SSI and the Drift Limit Required by International Codes

Type of foundation	Soil type	Drift (m) Dynamic analysis considering SSI				Drift limit calculated by codes		
		Fixed	Wolf	Gazetas	ECP 202-2007	EC-8	ECP 201-2012	IBC 2012
		D_F	D_W	D_G	D_{ECP}			
NSC with f_c' = 25 MPa								
Surface	S_1	.0195	.0274	.0284	.0275	.0365	.0365	.0365
	S_2	.0195	.0254	.0264	.0254			
	S_3	.0195	.0249	.0251	.0248			
Embedded	S_1	.0195	.0256	.0263	.0262			
	S_2	.0195	.0239	.0243	.0242			
	S_3	.0195	.0211	.0220	.0217			
HSC with f_c' = 75 MPa (reduced sections)								
Surface	S_1	.021	.0263	.0272	.0266	.0365	.0365	.0365
	S_2	.021	.0246	.0258	.0243			
	S_3	.021	.0243	.0242	.0237			
Embedded	S_1	.021	.0245	.0249	.0244			
	S_2	.021	.0221	.0226	.0233			
	S_3	.021	.021	.022	.0228			
HSC with f_c' = 75 MPa (constant sections)								
Surface	S_1	.0187	.0245	.0253	.0247	.0365	.0365	.0365
	S_2	.0187	.0237	.0233	.0234			
	S_3	.0187	.020	.0197	.0212			
Embedded	S_1	.0187	.0231	.0227	.0236			
	S_2	.0187	.0210	.0207	.0210			
	S_3	.0187	.0199	.0194	.0198			

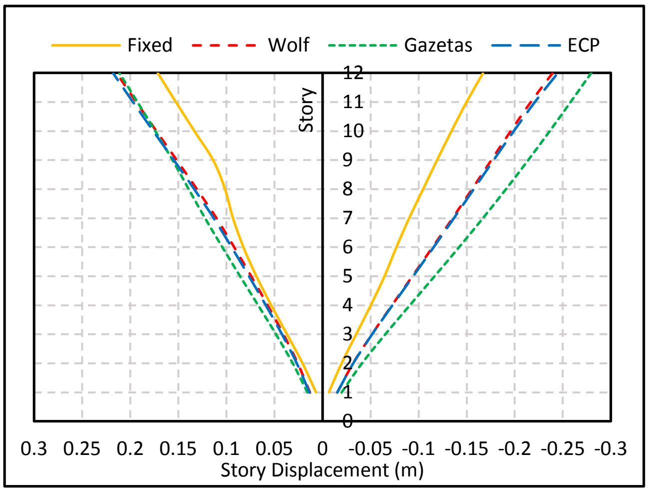


Fig. 8 Effect of the SSI on Envelops of Story Displacement for 12-Story Dual System Constructed from NSC with Surface Foundation Resting on Soft Soil (S1).

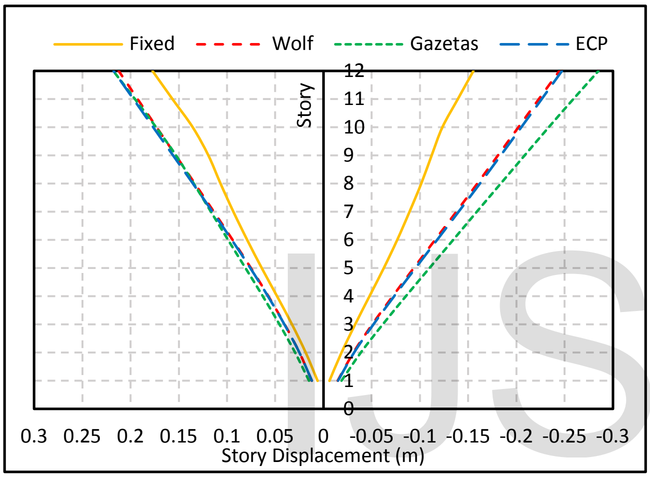


Fig. 9 Effect of the SSI on Envelops of Story Displacement for 12-Story Dual System Constructed from HSC (Reduced Sections) with Surface Foundation Resting on Soft Soil (S1).

9 CONCLUSIONS

Based on the results of this study, the following conclusion can be drawn:

- Upon employing the Wolf model in the analysis of the 12-story building frame, it is found that ignoring the SSI is associated with an underestimation of the roof displacement relative to that of the fixed base by 18%, 16%, and 15% for NSC, HSC (reduced sections) and HSC (constant sections), respectively, while for the IBC-2012 model these ratios are 13%, 15%, and 9%, respectively. For 12-story dual system, ignoring the SSI using Wolf model with soft soil results in an increase in the roof displacement relative to that of the fixed base by 39.8%, 38.4% and 9.3% for NSC and HSC (reduced sections) and HSC (constant sections), while for IBC-2012 model these ratios are 41.5%, 30%, and 23%, respectively.
- For the 12-story building frame, considering the SSI using Wolf model with soft soil increases the story drift by 19.25%, 28.1% and 18.4% for NSC and HSC (reduced sections) and HSC (constant sections), respectively, while for Gazetas model these ratios are 25.7%, 34.9%, and 21%, respectively. For the 12-story dual system, considering the SSI using Wolf model with soft soil results in an increase in the drift by 40.5%, 25.2% and 31% for NSC and HSC (reduced sections) and HSC (constant sections), respectively while for Gazetas model these ratios are 45.6%, 29.5%, and 35.2%, respectively.
- The calculated maximum story drift considering the SSI with soft soil S1 for the 12-story building frame constructed from HSC with fc' = 75 MPa exceeds the story drift limit required by the international codes by 7.4%, 13.2% and 6.5% for Wolf, Gazetas and ECP model, respectively. For the 12-story dual system the calculated maximum story drift is still within the limit of the international codes as a result of the large stiffness of the shear walls.
- Ignoring the SSI using Wolf model for the case of soft soil with the 12-story building frame resulted in an increase in the fundamental period by 13%, 13% and 18% for NSC and HSC (reduced sections) and HSC (constant sections), respectively, while for the IBC-2012 these ratios are 12%, 12%, and 18%, respectively. For the 12-story dual system, ignoring the SSI using the Wolf model with soft soil resulted in an underestimation of the period by 28%, 29.9% and 39.2% for NSC and HSC (reduced sections) and HSC (constant sections), respectively; while for the IBC-2012 these ratios are 47%, 42% and 61.4%, respectively.
- In calculating the base shear for soft soil with 12-story building frame, considering the SSI using Wolf model decreases the base shear relative to that of the fixed base by 27%, 20% and 11% for NSC, HSC (reduced sections) and HSC (constant sections), respectively, while for the IBC-2012 model these ratios are 15%, 13% and 13%, respectively. For 12-story dual system, considering SSI using Wolf model results in a reduction of the base shear relative to that of the fixed base by 13.8%, 24.4% and 24.8% for NSC, HSC (reduced sections) and HSC (constant sections), respectively while for IBC-2012 model these ratios are 10%, 18% and 18.7%, respectively.
- The seismic behavior of building frames and dual systems constructed from NSC and HSC considering the SSI using the ECP 202-2007 models gives approximately similar results to that of Wolf model, while Gazetas model gives the highest results.
- Considering the SSI for moment-resisting building frames and dual systems constructed from NSC and HSC and rested on stiff soil gives results generally similar to that of the fixed base condition and, consequently the SSI may be safely neglected in cases of stiff soil.
- The model proposed by the IBC-2012 for considering the SSI is relatively simple in application compared with the other studied models and generally gives results for the seismic behavior of building frames and dual systems similar to that of the Wolf model.

REFERENCES

[1] M. Moghaddasi, M. Cubrinovski, J. Chase, S. Pampanin, and A. Carr, “Effects of soil–foundation–structure interaction on seismic structural response via robust Monte Carlo simulation,”" Engineering Structures, 33(4), pp.1338-1347, 2011.

[2] H. Chinmayi, B. Jayalekshmi, " Soil-structure interaction effects on seismic response of a 16 story RC framed building with shear wall "American Journal of Engineering Research (AJER), Volume-2, pp-53-58, 2013.

[3] S. Raheem, M. Ahmed, and T. Alazrak, “Evaluation of soil–foundation–structure interaction effects on seismic response demands of multi-story MRF buildings on raft foundations,” International Journal of Advanced Structural Engineering (IJASE), 7(1), pp.11-30, 2014.

[4] G. Gazetas, “Formulas and charts for impedances of surface and embedded foundations,” Journal of Geotechnical Engineering, pp. 1363-1381, 1991.

[5] J. Wolf, “Foundation vibration analysis using Simple Physical Models,” Englewood Cliffs, Prentice-Hall, 1994.

[6] International Code Council, “International Building Code,” IBC, West Flossmoor Road, Country Club Hills, USA, 2012.

[7] Ministry of Housing, Utilities and Urban Communities, “Egyptian Code for Soil Mechanics and Foundation Design,” ECP-202, Cairo, Egypt, 2007.

[8] American Society of Civil Engineers, “Minimum Design Loads For Buildings and Other Structures,” ASCE, Reston, Virginia, 2010.

[9] S. Mazzoni, F. Mckenna, M. Scott, and G. Fenves, “OpenSees command language manual,” Pacific Earthquake Engineering Research (PEER) Center, 2006.

[10] Daniel, Cusson, and P. Patrick, “Stress-strain model for confined high-strength concrete,” Journal of Structural Engineering, V. 121, N0. 3, pp. 468-477, March 1995.

[11] ACI Committee 318. “Building Code Requirements for Reinforced Concrete and Commentary,” ACI 318-2014, ACI, Farmington Hills, MI, 2014.

[12] B. Massicotte, AE. Elwi, And IG. Mac Gregor, "Tension-stiffening model for planner reinforced concrete members" Journal of Structural Engineering, 116 (11), pp .3039–58.March 1995.

[13] Ministry of Housing, Utilities and Urban Communities, “Egyptian Code for Loads and Forces in Structural Works,” ECP-201, Cairo, Egypt, 2012.

[14] B. Wair, J. DeJong, and T. Shantz, "Guidelines for estimation of shear wave velocity profiles" PEER, 2012.

[15] European Committee for Standardization. Eurocode8, “Design of structures for earthquake resistance,” Brussels, 2005.

[16] T. Paulay, A. Carr, and D. Tompkins, “ Response of ductile reinforced concrete frames located in zone C,” Bulletin of the New Zealand National Society for Earthquake Engineering, V. 13, No. 3, pp. 209-225, September 1980.

[17] A. Kappos, “Analytical prediction of the collapse earthquake for R/C buildings,” Journal of Earthquake Engineering and Structural Dynamics, V.20, pp. 177-190, 1991.

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NOTATIONS

- B and L = half width and half-length of foundation
- G and υ = shear modulus and poisons ratio
- V_s and V_{la} = shear wave velocity and Lysmer's analog wave velocity
- ω = circular frequency
- β = foundation damping
- A = area of foundations
- I_{bx} and I_{by} = area moment of inertia about X and Y axis
- D, e = embedded height
- r_o = equivalent foundation radius
- γ and ϱ= unit weight and unit mass of soil
- K_z, K_H and K_r = spring stiffness for vertical, horizontal and rocking directions of surface foundations
- C_z, C_H and C_r = damping coefficient for vertical, horizontal and rocking directions of surface foundations
- K_{zemb}, K_{Hemb} and K_{remb} = spring stiffness for vertical, horizontal and rocking directions of embedded foundations
- C_{zemb}, C_{Hemb} and C_{remb} = damping coefficient for vertical, horizontal and rocking directions of embedded foundations
- $\overline{V}$ = Base shear considering SSI
- V = Base shear of fixed base
- $\overline{\delta}_x$ = roof displacement considering SSI
- δ_x = roof displacement of fixed base