ORIGINAL RESEARCH

Evaluation of soil–foundation–structure interaction effects on seismic response demands of multi-story MRF buildings on raft foundations

Shehata E. Abdel Raheem · Mohamed M. Ahmed · Tarek M. A. Alazrak

Abstract Soil conditions have a great deal to do with damage to structures during earthquakes. Hence the investigation on the energy transfer mechanism from soils to buildings during earthquakes is critical for the seismic design of multi-story buildings and for upgrading existing structures. Thus, the need for research into soil–structure interaction (SSI) problems is greater than ever. Moreover, recent studies show that the effects of SSI may be detrimental to the seismic response of structure and neglecting SSI in analysis may lead to un-conservative design. Despite this, the conventional design procedure usually involves assumption of fixity at the base of foundation neglecting the flexibility of the foundation, the compressibility of the underneath soil and, consequently, the effect of foundation settlement on further redistribution of bending moment and shear force demands. Hence the SSI analysis of multi-story buildings is the main focus of this research; the effects of SSI are analyzed for typical multi-story building resting on raft foundation. Three methods of analysis are used for seismic demands evaluation of the target moment-resistant frame buildings: equivalent static load; response spectrum methods and nonlinear time history analysis with suit of nine time history records. Three-dimensional FE model is constructed to investigate the effects of different soil conditions and number of stories on the vibration characteristics and seismic response demands of building structures. Numerical results obtained using SSI model with different soil conditions are compared to those corresponding to fixed-base support modeling assumption. The peak responses of story shear, story moment, story displacement, story drift, moments at beam ends, as well as force of inner columns are analyzed. The results of different analysis approaches are used to evaluate the advantages, limitations, and ease of application of each approach for seismic analysis.

Keywords Soil–structure interaction · Seismic design · Egyptian building code · Time history analysis · Moment-resistant multi-story building · Raft foundation

Introduction

Over the past 40 years, considerable progress has been made in understanding the nature of earthquakes and how they could cause structure damages, and in improving the seismic performance of the built environment. However, much remains unknown regarding the prevention or mitigation of earthquake damage in worldwide, leaving room for further studies. During the past and recent earthquakes, it is realized that the soil–structure interaction (SSI) effects play an important role in determining the behavior of building structures. The seismic excitation experienced can be considered a function of the fault rupture mechanism, travel path effects, local site effects, and SSI effects (Gu 2008). Irrespective of the structure, the local soil conditions can dramatically influence the earthquake motion from the bedrock level to the ground surface, through their dynamic filtering effects. One example is the 1985 Mexico City earthquake where deep soft soils amplified the ground motion and modified the frequency of ground shaking.

S. E. Abdel Raheem (✉)
Civil Engineering Department, Faculty of Engineering, Taibah University, Madinah, Kingdom of Saudi Arabia
e-mail: shehataraheem@yahoo.com

S. E. Abdel Raheem · M. M. Ahmed
Civil Engineering Department, Faculty of Engineering, Assiut University, Assiut, Egypt

T. M. A. Alazrak
Faculty of Engineering, Sohag University, Sohag, Egypt

Similar behavior was observed during the 1989 Loma Prieta earthquake, in which the sections of the Cypress freeway in Oakland collapsed due to the soil-related motion amplification. Common practice of analysis and design of buildings is to assume the base of building to be fixed, whereas in reality supporting soil influences the structural response by permitting movement to some extent due to its natural ability to deform. The seismic SSI of multi-story buildings becomes very important after the destruction of recent major earthquakes. For the structure founded on the soil, the motion of the base of the structure will be different from the case of fixed base, because of the coupling of the structure–soil system. It is true that taking the soil into account when calculating the seismic response of the structure does complicate the analysis considerably. It also makes it necessary to estimate additional key parameters, which are difficult to determine, such as the properties of the soil, foundation and their interaction. The seismic response of the bridge with SSI under bi-directional earthquake excitations considering different soil flexibilities is investigated by many researchers (Abdel Raheem et al. 2002, 2003; Abdel Raheem and Hayashikawa 2003; Hayashikawa et al. 2004; Soneji and Jangid 2008; Shah et al. 2011). The emphasis has been placed on assessing the significance of soil behavior that affects the response of the system and identifies the circumstances under which it is necessary to include the SSI effects in the design of bridge structures. In seismic design of buildings, the consequences of soil flexibility are generally ignored. Mylonakis et al. (1997) and Roy (2001) showed the possible severities of neglecting the effects of the SSI in their studies. Similar study on implication of neglecting the SSI in ensuring the structural safety by conventional elastic and inelastic design procedure of moment-resisting building frames was shown by Tabatabaiefar et al. (2013).

This research aims to study the SSI for multi-story buildings on raft foundation, evaluate the approach of Egyptian Code seismic provisions for analysis methods during the seismic design of buildings, discuss the alternative solutions for cases wherein existing provisions do not lead to satisfactory results and to quantify the effect SSI on the structural response so that designers can be aware of the likely impact of their decisions. Time history analysis (TH) has been performed to evaluate equivalent static load (ESL) and the response spectrum (RS) analysis methods; a set of time history records has been used. A parametric study with different approaches of analysis, design parameters of the underneath soil conditions and number of stories is carried out to evaluate the SSI effects on the building vibration characteristics and seismic demands including the fundamental period, total base shear, story displacements, story drifts, moment at beams ends and force of inner columns. The results show that SSI has a significant influence on the seismic response demands.

Egyptian code seismic design provisions

The great losses due to Cairo earthquake on October 1992 (Ms 5.4) were mainly related to the fact that at the time of construction, the buildings were designed to resist only vertical loads and had insufficient lateral resistance. Thus, the columns and beam column connections were found to have inadequate shear capacity, ductility and confinement in plastic hinges (El-Arab 2011; Abdel Raheem et al. 2010, 2014a, b). This earthquake illustrated the vulnerability of the building stock, especially older structures, due to design, detailing, construction and maintenance issues (Khater 1992; Badawi and Mourad 1994; Mourad et al. 2000). So there is an urgent need for assessment of existing buildings in terms of seismic performance and continuously upgrades the seismic codes for design of new buildings. The design of structures for earthquakes became a major demand enforced in the Egyptian design codes that motivated the Ministry of Housing and Buildings to update the Egyptian codes regularly, to take into account the seismic loads into consideration. Since October 1992, a set of Egyptian codes have been released to prevent buildings' collapse and/or control major damages of structural elements (ECP 1993, 2001, 2004a, b, 2007, 2008). Many advances in earthquake engineering have been made from the observation of the performance of real structures that have been subject to a severe earthquake, analytical modeling, including finite element analysis, FEA, has an important role, but its limitations must be recognized. For many engineered structures, satisfactory seismic performance requires careful attention to analysis, design, and detailing and good construction practice. Safety is thus achieved by the successful integration of analysis, design and construction.

Building code restrictive seismic design provisions and building systems type and configuration have remarkable implications on seismic performance of reinforced concrete moment-framed structures. The specifications permit the designer to utilize a variety of methods for seismic analysis that range from simple equivalent static analysis to complex nonlinear dynamic analysis (UBC 1997; AIJ 1999; SEAOC 1999; ICC 2003; ECS 2004; ASCE 2005; ECP 2007, 2008). For building structures, it is common practice to utilize a simplified approach, such as ESL. This approach has several shortcomings, which have been accepted due to its simplicity and a lack of alternative practical approaches (Abdel Raheem 2013). Such approach may be regarded as force-based since the methods' primary emphasis is on the forces within the structure. In recent years, there has been a shift of attention away from linear methods of seismic analyses to nonlinear methods which put emphasis on the displacements within the structure. Thus, nonlinear analysis methods that are capable of

realistically predicting the deformations imposed by earthquakes on structures are needed. In response to this need, nonlinear static analysis procedures have appeared in national resource documents such as the ATC-40 and ATC3-06 reports on seismic evaluation and retrofit of concrete buildings and seismic regulation for buildings (ATC 1978, 1996; Goel and Chopra 1997) and the FEMA-356 pre-standard on seismic rehabilitation of buildings (FEMA 2000, 2007). Such analysis methods are useful for predicting inelastic displacement capacities while simultaneously offering a compromise between the oversimplification of linear static analysis and the inherent complexity of nonlinear dynamic analysis. The latest Egyptian Code for Load and Forces (ECP 2008), and most of the international participating building codes, depends on the traditional approach of ESL method as a main method for evaluating seismic actions on symmetrical buildings (UBC 1997; AIJ 1999; ECS 2004; ECP 2008). For non-symmetrical buildings, the ECP-201 (ECP 2008) recommended the response spectrum method to be used for building seismic analysis and design, which considered more accurate method of analysis than the ESL method (Chopra 1995; Paz and Leigh 2003).

Egypt is suffered a numerous of destructive earthquakes as well as Kalabsha earthquake (1981, Ms 5.4) near Aswan city and the High dam, Dahshour earthquake (1992, Ms 5.9) near Cairo city and Aqaba earthquake (1995, Ms 7.2). As the category of earthquake damage includes all the phenomena related to the direct and indirect damages, the Egyptian authorities do a great effort to mitigate the earthquake disasters. The seismicity especially at the zones of high activity is investigated and the soil condition, soil amplification, soil structure interaction, liquefaction and seismic hazard are carried out, in particular the urbanized areas. All these parameters are integrated to obtain the Egyptian building code which is valid to construct buildings resist damages and, consequently, mitigate the earthquake disasters. A prevailing common conclusion of several studies is that SSI could produce significant effects on the seismic response of structures: both beneficial and detrimental effects were reported. Nevertheless, utilization of the findings of these research efforts in national and international design codes and in routine design calculations is still very rare if not absent.

Alternative procedures for seismic analysis and design

In the preliminary design process, equivalent static seismic forces are used to determine the design internal forces of structural members using linear elastic analyses of structure and, in turn, determine the design member strength demands. Such static seismic forces are simply determined corresponding to the elastic design acceleration spectrum divided by a structural strength reduction factor particularly called: the response modification factor, R (ECP 2008; UBC 1997); the structural behavior factor, q (ECS 2004); or the structural factor, D_s (AIJ 1999). Usually, the elastic design spectrum, which is often related to 5 or 10 % probability of exceedance (POE) in 50 years, is defined smoothly as a reasonable representation of the seismic action demand on the structure at the site of interest. The adopted strength reduction factor is thus intended to represent an expected inelastic response demand or expected damage level demand of the whole structure, which may be induced during earthquake excitation (Thuat 2012).

All design against earthquake effects must consider the dynamic nature of the load. However, for simple regular structures, analysis by equivalent linear static methods is often sufficient. This is permitted in most codes of practice for regular, low- to medium-rise buildings and begins with an estimate of peak earthquake load calculated as a function of the parameters given in the code. Equivalent static analysis can, therefore, work well for low- to medium-rise buildings without significant coupled lateral–torsional modes, in which only the first mode in each direction is of significance. Tall buildings, where second and higher modes can be important, or buildings with torsional effects, are much less suitable for the method, and both Eurocode 8 (ECS 2004) and IBC (ICC 2003) require more complex methods to be used in these circumstances. With the advent of powerful desktop computers, the modal response spectrum analysis has become the norm. It involves calculating the principal elastic modes of vibration of a structure. The maximum responses in each mode are then calculated from a response spectrum and these are summed by appropriate methods to produce the overall maximum response. The major advantages of modal response spectrum analysis (RS), compared with the more complex time history analysis described later, are as follows. The size of the problem is reduced to finding only the maximum response of a limited number of modes of the structure, rather than calculating the entire time history of responses during the earthquake. This makes the problem much more tractable in terms both of processing time and (equally significant) size of computer output. Examination of the mode shapes and periods of a structure gives the designer a good feel for its dynamic response. The use of smoothed envelope spectra makes the analysis independent of the characteristics of a particular earthquake record. RSA can very often be useful as a preliminary analysis to check the reasonableness of results produced by linear and non-linear time history analyses.

Offsetting these advantages are the following limitations: RS is essentially linear and can make only approximate allowance for nonlinear behavior. The results are in

terms of peak response only, with a loss of information on frequency content, phase and number of damaging cycles, which have important consequences for low-cycle fatigue effects. Moreover, the peak responses do not generally occur simultaneously; for example, the maximum axial force in a column at mid-height of a moment-resisting frame is likely to be dominated by the first mode, while its bending moment and shear may be more influenced by higher modes and hence may peak at different times. It will also be recalled that the global bending moments calculated by RSA are envelopes of maxima not occurring simultaneously and are not in equilibrium with the global shear force envelope. Variations of damping levels in the system between the structure and the supporting soils can only be included approximately. Modal analysis as a method begins to break down for damping ratios exceeding about 0.2, because the individual modes no longer act independently. The method assumes that all grounded parts of the structure have the same input motion. This may not be true for extended systems, such as long pipe runs or long-span bridges. A time history analysis overcomes all the disadvantages of RS, provided the nonlinear behavior is not involved. The method involves significantly greater computational effort than the corresponding RSA and at least three representative earthquake motions must be considered to allow for the uncertainty in precise frequency content of the design motions at a site. With current computing power and software, the task of performing the number crunching and then handling the large amount of data produced has become a non-specialist task.

Equivalent static load method

The structural response is a function of building mass, stiffness, and material damping (Ghosh and Fanella 2003; Abdel Raheem et al. 2010); however, ECP-201 (ECP 2008) gives an empirical expression to calculate the ESL of seismic action depending on the total building weight only, neglecting the effect of building stiffness and material damping on the structural response. According to ECP-201 (ECP 2008), the seismic base shear force, F_b, for each horizontal direction in which the building is analyzed shall be determined using the following expression:

$$F_b = S_d(T_1) \times \lambda \times W/g \tag{1}$$

where $S_d(T_1)$ is the ordinate of the design spectrum at period T_1; T_1 is the fundamental period of vibration of the building for lateral motion in the direction considered; W is the total weight of the building, above the foundation level; g is the gravity acceleration; λ is the effective modal mass correction factor, the value of which is equal to: $\lambda = 0.85$ for $T \leq 2 T_c$, and $n > 2$ stories, where n is number of stories; T_c is the upper limit of the period of the constant

spectral acceleration branch as shown in Fig. 1. The value of the fundamental period of vibration, T, is determined using the following expression:

$$T = C_t \times H^{3/4} \tag{2}$$

where C_t is a factor determined according to the structural system and building material and equal to 0.075 in case of moment-resistant space concrete frame; H is the height of the building (m), from the foundation or from the top of a rigid basement. The ordinate of the design spectrum, S_d (T_1), can be determined from:

$$s_d(T) = \frac{2.5}{R} \times a_g \times \gamma \times S\left[\frac{T_c}{T}\right] \geq [0.2] \times a_g \times \gamma \tag{3}$$

where a_g is the design ground acceleration for the reference return period; T_c is the upper limit of the period of the constant spectral acceleration branch as shown in Fig. 1; S is the soil factor. γ is the importance factor. R is the reduction factor according to the statical system of the structure. The total base shear, F_b, shall be determined by applying horizontal forces F_i to each story mass m_i and shall be distributed as follows:

$$F_i = \left[\frac{z_i \times W_i}{\sum_{j=1}^{n} z_j \times W_j}\right] \times F_b \tag{4}$$

where F_i is the horizontal force acting on story i; F_b is the seismic base shear force (Eq 2); z_i and z_j are the heights of the masses m_i and m_j above the foundation level, respectively; W_i and W_j are the weights of masses m_i and m_j; n is the number of stories above foundation level. Equation 5 gives linear shear distribution depending on the story height.

Response spectrum method

The response spectrum analysis is applicable for all types of buildings, while the lateral force method of analysis has many restrictions on its use due to the 'fear' that it would provide un-conservative results in certain conditions;
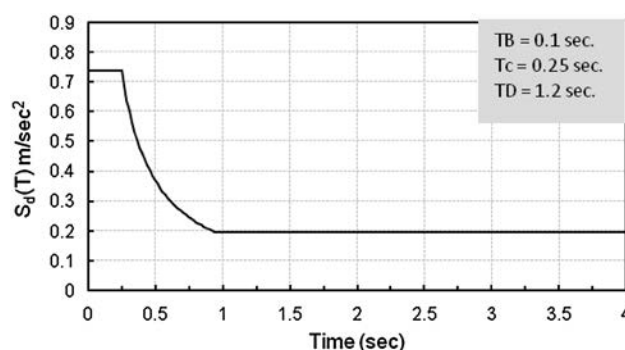

Fig. 1 ECP-201 (ECP 2008) design response spectrum

however, in spite of this disadvantage the method is still widely used due to its ease of application (Crowley and Pinho 2010). Response spectrum analysis includes sufficient modes of vibration to capture participation of at least 90 % of the structure's mass in each of the two orthogonal directions (Kunnath and Kalkan 2004). Figure 1 shows the design response spectrum curve for current case of study; it shall be noted that, ECP-201 (ECP 2008) includes a damping coefficient in the elastic response spectra equations. Hence, no damping ratio has been used in the analysis of this method. As specified in the most design codes, the shape of the target elastic acceleration spectrum is characterized by the seismic intensity expressed in terms of the expected design peak ground acceleration (PGA), a_g, and the effect of soil ground types expressed in terms of the response spectral periods T_b and T_c. Various values of T_b and T_c were considered corresponding to different soil ground types (from A-type of hard rock to D-type of soft soil).

Many codes recognize that the period of vibration from the simplified period–height equation is more realistic, having been directly obtained from the measured periods of vibration of buildings subject to earthquake ground motions, but that when higher modes are important (in tall and/or irregular structures) the modal response spectrum method gives a more realistic profile of the lateral forces. Hence, these codes (ECP 2008; NBCC 2005; ASCE 2005) require the designer to check whether the modal base shear force is less than 85 % of the base shear force from the equivalent static force method. If this is the case, then the modal forces, but not the drifts, should be multiplied by 0.85 V/V_t where V is the base shear from the lateral force method and V_t is the base shear from the required modal combination. Even when higher modes are not important and the designers are allowed to use the linear static method, but they decide to calculate the period of vibration from the Rayleigh method, many codes apply an upper bound to the period of vibration from the Rayleigh method. This is another procedure which is used to safeguard against unrealistically high periods of vibration used in the design to lower the base shear forces (Crowley and Pinho 2010).

The seismic zone considered in this study is zone 1 and the shape of spectrum is type 1 as per Egyptian zoning system with design ground acceleration, a_g of 0.1 g associated with the code reference probability of exceedance of 10 % in 50 years as shown in Fig. 1. The two models are considered as a residential buildings with importance factor $\gamma = 1$. The soil class is considered "C" and a soil factor $S = 1.5$. The reduction factor, R, is taken considering the vertical loads and the total base shear is totally resisted by the frame structure without using shear walls or bracings ($R = 5$). It should be noted that ECP-201 (ECP 2008) recommends that in the application of the ESL method, the building should meet the criteria for regularity in both plan and elevation, and with calculated structural period T not greater than 2 s or 4Tc (1 s for the selected soil class "C"). In ESL method, according to ECP-201 (ECP 2008), a total seismic mass including self-weight and floor cover plus 25 % of live load is considered. The base shear is determined as a percentage of the total building weight that gives a value of 2.58 % in 6-story building and 1.82 % in 12-story building.

Nonlinear time history (TH) method

Nonlinear time history analysis is by far the most comprehensive method for seismic analysis. The earthquake record in the form of acceleration time history is input at the base of the structure (Kharade et al. 2013). The response of the structure is computed at each second for the entire duration of an earthquake. This method differs from response spectrum analysis because the effect of "time" is considered. That is, stresses and deformations in the structure at an instant are considered as an initial boundary condition for computation of stresses in the next step. Furthermore, nonlinearities that commonly occur during an earthquake can be included in the time history analysis. Such nonlinearities cannot be easily incorporated in response spectrum analysis. Unlike the response spectrum method, nonlinear time history analysis does not assume a specific method for mode combination. Hence, results are realistic and not conservative. Furthermore, this method is equivalent to getting 100 % mass participation using response spectrum analysis. Full mass participation is necessary to generate correct earthquake forces. Usually, only 90–95 % participation is obtained in response spectrum analysis. All types of nonlinearities can be accounted for in this analysis. This could be very important when seismic retrofit involves energy dissipation using yielding of members or plastic hinge rotation. However, this method is very expensive and time consuming to perform. Large amounts of information are generated. Furthermore, input earthquake is never known with certainty. Hence, three to five different histories should be used, further increasing the cost. The equation of motion for a system subjected to earthquake excitations can be written as (Algreane et al. 2011; Abdel Raheem and Hayashikawa 2013):

$$[M]\ddot{u} + [C]\dot{u} + [K]u = F(t) \tag{5}$$

where M, C and K are the mass; damping and stiffness matrices, respectively. F (t) is the seismic excitation, and u, $\dot{u}$ and u are accelerations, velocities and displacements' time-dependent vectors, respectively. Since the results of the time history depend mainly on the characteristic of the used acceleration time history records and the shapes of

their corresponding elastic response spectra (Kunnath and Kalkan 2004), the reason of using the inelastic TH method is to verify the results obtained by other code-specific analysis procedures (ESL and RS methods) against a time history record. Nonlinear time history analysis was performed taking into consideration the P-Δ and large displacements' effect. A constant damping ratio of 0.05 has been taken for RC buildings. The inelastic time history analysis is preformed using the direct integration technique considering a time step of 0.005 s. Nonlinear analysis could be used to justify a design that would not satisfy the prescriptive building code requirements. Story drifts and floor accelerations are important indicators of damage to nonstructural components and overall building performance. For nonlinear seismic analyses, a total mass including self-weight and floor cover "Dead Load; DL" plus 25 % of Live Load "LL" (1.0DL + 0.25LL) is considered (ECP 2008).

Finite element analysis and modeling technique

Target multi-story MRF building description

During the past two decades, the building environment in Egypt had extensively utilized medium-rise R.C. buildings having twelve stories, the maximum height allowed by the local authorities in most districts. These building are built with different configurations and structural systems having varying stiffness parameters that may have great influence on their seismic behavior. Two samples for typical buildings with six and twelve stories are chosen for this study as shown in Fig. 2; building's layout is essentially bi-symmetric in plan, and regular plans of four equal bays with a typical bay width of 5 m in both directions, and is representative of benchmark typical buildings in current practice in Egypt. The height of every story (column height) is taken equal to 3 m, as a normal height for residential buildings. Beams are assumed on all grid lines. The building structural elements have been first designed according to Egyptian code of practice (ECP 2007, 2008) under static loads assuming un-cracked sections for beam and slabs in the analysis. Slab thickness was taken 15 cm and beam section was taken 30×60 cm. These sections have been checked under seismic actions using the Egyptian code for load and forces (ECP 2008) to satisfy the Egyptian code requirements taking into consideration the effect of earthquake loads. The minimum safe column cross section under static and dynamic loads, to satisfy the Egyptian code requirements (ECP 2007, 2008), is 0.6×0.6 m for 6-story building and 0.8×0.8 m for 12-story building. The materials used in the design are C250 for concrete and St52 for steel; the material for the

building structure is taken as a reinforced concrete with constant properties of modulus of elasticity $E = 2.21 \times 10^6$ t/m^2, Poisson ratio $\mu = 0.2$, density of concrete = 2.5 t/m^3, compressive strength $f_c = 2,500$ t/m^2, and yield strength $f_y = 36,000$ t/m^2. For gravity load design, dead loads include the self-weight of the structure, a typical floor cover of 0.15 t/m^2 and partition (wall) loads' intensity of 1 t/m^2 on all beams including plastering and assuming typical walls thickness of 0.25 m. The model is assumed to be a residential building with live load =0.2 t/m^2.

Raft foundation and soil conditions

For understanding the importance of effect of soil structure interaction on the seismic response of multi-story buildings, this study attention focuses on evaluating the seismic response of reinforced concrete multi-story buildings on raft foundation with thickness equal to 0.6 m for 6-story building and 1.0 m for 12-story building. The underneath soil is modeled by Winkler spring approach with equivalent static stiffness based on soil modulus of elasticity of range from 24,480, 12,240 and 6,120 t/m^2 for stiff, medium and soft soil (ASTM 1985). The soil spring stiffness can be given as (Gazeteas 1991; Mylonakis et al. 2006; Kalkan and Chopra 2010):

$$K_z = \frac{Gl}{1-v}\left[0.73 + 1.54\left(\frac{B}{L}\right)^{0.75}\right] \tag{6}$$

$$K_y = \frac{GL}{2-v}\left[2 + 2.5\left(\frac{B}{L}\right)^{0.85}\right] \tag{7}$$

$$K_x = K_y - \frac{0.2}{0.75-v}GL\left(1 - \frac{B}{L}\right) \tag{8}$$

$$G = \frac{E}{2(1+v)} \tag{9}$$

where G is shear modulus of soil, E is the modulus of elasticity of soil; v is the Poisson's ratio of soil. L and B are the length and width of foundation, respectively. The elastic properties and stiffness of soil spring for stiff, medium and soft soil are given in Table 1.

Mathematical model and finite element solution

A three-dimensional mathematical model of the physical structure will be used that represents the spatial distribution of the mass and stiffness of the structure to an extent that is adequate for the calculation of the significant features of the building's dynamic response. The building is modeled as 3D frame structure using frame elements for columns, longitudinal beams and transverse beams, shell element for slabs and raft and spring element for soil. With the
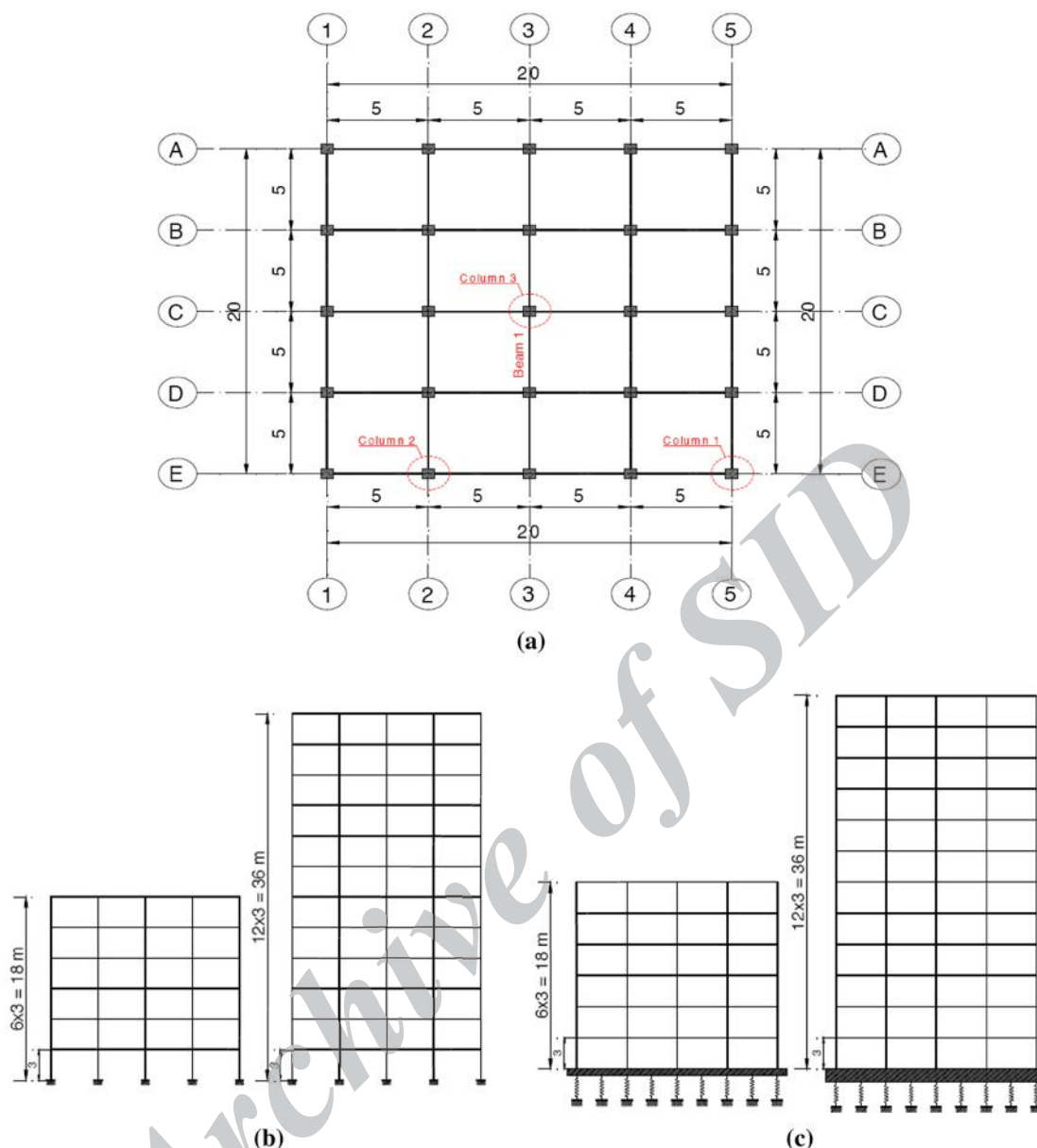
Fig. 2 Configuration of 6-story and 12-story building models. **a** Plan configuration, **b** elevation of fixed base model "NSSI model" and **c** elevation of soil structure interaction model "SSI model"

Table 1 Elastic Properties and stiffness of soil area spring element

Soil condition	Poisson's ratio v	Modulus of elasticity E (t/m²)	K_x (t/m²/m)	K_y (t/m²/m)	K_z (t/m²/m)
Stiff soil	0.33	24,480	1,127.21	1,127.21	1,417.29
Medium soil	0.33	12,240	563.6	563.6	708.64
Soft soil	0.33	6,120	281.8	281.8	354.32

mathematical model chosen, finite element procedures are used to solve the model. All structures are modeled and analyzed in this paper using ETABS and Sap2000 (Computers and Structures Inc 2003, 2007, 2011a, b). The

damping in the models is considered to be 5 % of the critical; the same damping is used in the codified approaches.

Input ground motion excitation

It is impossible to predict ground motion characteristics that may occur in the future at a construction site because the property of the ground motion is interrelated with many factors, such as fault mechanism, seismic wave propagation from source to site and the amplification characteristics of ground. The important factors of ground motions affecting structure's response

results are peak ground acceleration, frequency contents, duration of ground motion and shapes of waveform. Egypt is a region of moderate seismicity, where infrequent moderate to large earthquakes have occurred in the past. However, there is a serious lack of strong motion records of engineering interest in the region. Therefore, the use of a large number of artificial or natural earthquake records from the literature is indispensible for the nonlinear time history analysis. The seismic design guidelines provide an acceleration response spectrum for estimating the design seismic force of a structure. Accordingly, the input ground motion applied to the dynamic response analysis of structures would be appropriate for the ground motion history which is highly related with design seismic force. A suite of nine-ground motion records from seven different earthquakes (PEER 2012) is selected for the purpose of understanding the input ground motion effect, as listed in Table 2.

A suite of nine-ground motion acceleration time history records, representing a wide range of intensity and frequency contents, is selected and used in the study. Those records are downloaded from the website of the Pacific Earthquake Engineering Research Center (PEER 2012). The earthquakes' records are listed in Table 2 by their magnitude, peak ground acceleration (PGA), peak ground velocity (PGV) and peak ground displacement (PGD). Figure 3 shows the elastic pseudo-acceleration response spectra of the earthquake motions for 5 % damping; the plot shows significant variation in the frequency contents and the response characteristics. The ground motion records are grouped into three levels depending on the peak ground acceleration as: low (0.1 g up to 0.3 g), moderate (0.4 g up to 0.6 g) and high (0.6 g up to 1.04 g). The records are chosen such that the period ratio (T_1/T_g and T_2/T_g; adjacent buildings period over the ground motion characteristic period) has a wide range.

Numerical results and discussions

Finite element modeling and numerical analysis are formulated to quantify the effects of soil-structure interaction and foundation flexibility on the structural response demands of MRF multi-story buildings on raft foundation so that designers can be aware of the likely impact on their decisions. The seismic response demands are compared for different alternative analysis methods based on Egyptian Code seismic provisions for seismic design; hence, alternative solutions are recommended for cases wherein existing provisions do not lead to satisfactory results. Time history analysis (TH) has been performed to evaluate ESL and the Response Spectrum analysis methods; a set of time history records has been used. A parametric study is carried out to evaluate the design parameter effects on the building seismic demands in different approaches of analysis and to assess the fundamental period, total base shear, displacements and story drifts for the three methods of analysis. The design parameters include the SSI with three types of soil and raft thickness.

In this paper, 6-story and 12-story building models are studied with two different modeling approaches: the first modeling approach includes raft foundation, soil and superstructure interaction (SSI model), while the second modeling approach considers over-ground portion of building based on fixed base-rigid foundation/rigid soil hypothesis (NSSI model/fixed base model). Based on the outcome results of the numerical study, the effects of SSI on the design parameters and seismic response demands including fundamental period, base shear, displacement, story drift, moments at beam ends and inner force of column are evaluated. A constant beam, slab, and column sections with rigid diaphragm assumption are considered in the analysis with different soil spring stiffnesses which present in different modulus of elasticity of soil as shown in Table 3. To study the SSI, fundamental period, base shear, displacement and story drift moments at beam ends, as well as inner force of column in the two models are compared. For convenience, response ratio is defined as

Table 2 Characteristics of earthquake ground motion records used in the analysis

Level	PGA (g)	Input wave	M_w	Earthquake/Station	Scale factor	EPD (km)	PGV (cm/s)	PGD (cm)	T_g (s)
Low	0.21	1MVH	6.0	N. Palm Springs, 1986/Morongo Valley	1.5	10.1	40.9	15.0	1.90
	0.30	2A-GRN	6.0	Whittier narrows, 1987/E-Grand Ave	1.7	9.0	23.0	3.3	0.70
	0.29	3G06	6.2	Morgan Hill, 1994/Gilroy Array #6	1.0	11.8	36.7	6.1	1.20
Moderate	0.48	4CYC	6.9	Loma Prieta, 1989/Coyote Lake Dam	1.2	21.8	39.7	15.2	0.65
	0.51	5STG	6.9	Loma Prieta, 1989/Saratoga-Aloha Ave	1.0	11.7	41.2	16.2	1.80
	0.59	6NPS	6.0	N. Palm Springs, 1986/5070	0.7	8.2	73.3	11.5	1.10
High	0.60	7D-PVY	5.8	Coalinga, 1983/Pleasant Valley P.P.	1.7	17.4	34.8	8.1	0.65
	0.84	8RRS	6.7	Northridge, 1994/Rinaldi	0.6	7.1	166.1	28.8	1.05
	1.04	9CPM	7.1	Cape Mendocino, 1992/Cape Mendono	0.6	8.5	42.0	12.4	2.00

Fig. 3 Associated 5 %-damped response spectrum for nine records
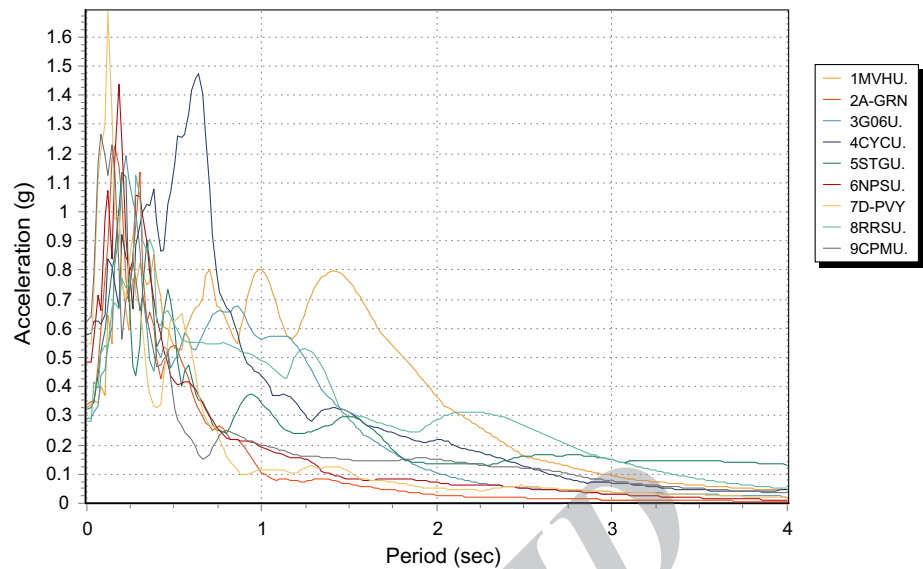

Table 3 Building structural element dimensions for different modulus of elasticity of soil models

Model	Beam size (cm)	Slab thickness (cm)	Column (cm)	Raft thickness (cm)	Soil modulus of elasticity (t/m^2)
6-story					
NSSI-1	25 × 60	15	60 × 60	Fixed base	N.A
SSI-1				60	24,480
SSI-2				60	12,240
SSI-3				60	6,120
12-story					
NSSI-2	25 × 60	15	80 × 80	Fixed base	N.A
SSI-4				100	24,480
SSI-5				100	12,240
SSI-6				100	6,120

below: Response ratio = (peak response of structure in soil structure interaction model)/(peak response of structure in fixed-base model).

Free vibration analysis

The period of vibration is a fundamental parameter in the force-based design of structures as this parameter defines the spectral acceleration and thus the base shear force to which the building should be designed. This study takes a critical look at the way in which seismic design codes around the world have allowed the designer to estimate the period of vibration for use in both linear static and dynamic analyses. In the most building design projects, empirical building period formulas are used to initiate the design process (Kwon and Kim 2010). The fundamental period of vibration, *T*, is a function of the stiffness of the lateral load resisting system and the building mass. The fundamental period in ECP-201 (ECP 2008), *T,* does not influence by the change of SSI but depends only on the building height. Table 4 introduces different fundamental periods, for the buildings studied, as obtained from structural analysis using finite element models and empirical expression in ECP-201 (ECP 2008) and other international building codes. In both 6-story and 12-story buildings, the periods computed from empirical expressions are significantly shorter than those computed from structural models, especially for building structures with soft soil spring stiffness. As the buildings' soil spring stiffness decreases; the fundamental period increases. Table 4 shows the disparity between the fundamental period of vibration from empirical period–height equation from different codes and the period of vibration from eigenvalue or Rayleigh analysis of a bare frame model. The fundamental period estimated by ECP-201 empirical equation is underestimated, especially for flexible models; the fundamental period reaches 183 and 236 % in models SSI3 and SSI6, respectively. Many codes recognize that the period of vibration from the simplified period–height equation is more realistic, having been directly obtained from the measured periods of vibration of buildings subject to earthquake ground motions, but that when higher modes are important (in tall and/or irregular structures) the modal response spectrum method gives a more realistic profile of the lateral forces (Abdel Raheem 2013). However, the empirical equation should be calibrated to obtain a conservative estimate for the base shear. As the buildings' soil stiffness decreases, fundamental period response ratio increases. Fundamental period response ratio is higher than 1.0,

Table 4 Fundamental period of the RC moment-resisting frame building

Code	Period, T	Fundamental period (sec)							
		NSSI-1	SSI-1	SSI-2	SSI-3	NSSI-2	SSI-4	SSI-5	SSI-6
3D model natural vibration analysis		0.98	1.07	1.12	1.21	1.92	2.15	2.32	2.60
Fundamental period response ratio		–	1.09	1.14	1.23	–	1.12	1.21	1.36
ECP-201 (ECP 2008)	$T = 0.075\ H^{3/4}$	0.66				1.10			
ECP-201 (ECP 1993)	$T = 0.1\ N$	0.61				1.20			
IBC (ICC 2003)	$T = 0.073\ H^{3/4}$	0.64				1.07			
UBC (UBC 1997)	$T = 0.049\ H^{3/4}$	0.43				0.72			
EC8 (ECS 2004)	$T = 0.075\ H^{3/4}$	0.66				1.10			
NBCC (NBCC 2005)	$T = 0.05\ H^{3/4}$	0.44				0.74			

H is the building height above the foundation level (m) and N is the number of the stories

ranging from 1.09 to 1.23 for 6-story model and from 1.12 to 1.36 for 12-story model, as shown in Table 4.

Seismic response analysis

Story drift ratio response

Story drift ratio is the maximum relative displacement of each floor divided by the height of the same floor and is an important parameter that has been evaluated. The story drift ratio response demands are investigated for studied multi-story building of 6- and 12-story using different analysis methods based on Egyptian Code seismic provisions for seismic design. The story drift ratio over the building's height for different soil condition range from stiff, medium to soft soils along with ration of the response of the SSI model to that of fixed-base model are introduced in Figs. 4, 5 for 6-story building and Figs. 6, 7 for 12-story building. The seismic response demands are calculated using ESL, RS and average envelope of TH of the nine records.

Figure 4a, b, c and d shows that story drift ratio distribution of 6-story model increases gradually and reaches its maximum value in the 2nd story level. The maximum values in NSSI-1, SSI-1, SSI-2 and SSI-3 using ESL method are 0.00081, 0.00089, 0.00094 and 0.00102, respectively. The maximum values in NSSI-1, SSI-1, SSI-2 and SSI-3 using response spectra (RS) method are 0.00055, 0.00086, 0.00089 and 0.00095, respectively. The average values of using time history method of nine earthquake ground motion records are 0.00115, 0.00122, 0.00122 and 0.0013, respectively. As the soil stiffness decreases; the story drift ratio increases. The story drift values calculated by TH method have higher values than ESL and RS methods, while those obtained by RS have lower values for story drift.

Figure 5a, b and c shows the story drift ratio response distribution over building height compared to that response value of fixed-base model for 6-story model. The story drift ratio increases over the building height as the supporting

soil changes from stiff to soft condition. This increasing trend is more significant in the upper and lower stories. The maximum response ratios of SSI-1, SSI-2 and SSI-3 compared to those of fixed base model using ESL method are 1.24, 1.39 and 1.66, respectively. The maximum response ratios of SSI-1, SSI-2 and SSI-3 compared to those of fixed base model using response spectra method (RS) are 1.74, 1.89 and 2.14, respectively. The average values of using time history method (Av-TH) of nine earthquake ground motion records are 1.22, 1.35 and 1.49, respectively. As the soil stiffness decreases, the story drifts ratio response ratio increases. Lower and upper stories are more affected with SSI than middle stories. The story drift ration increase for flexible raft foundation and as the underneath soil condition changes from stiff to soft soil. The greatest story drift ratio increase occurs for the structures located on the soft soil.

Figure 6a, b, c and d shows that story drift ratio distribution of 12-story model increases gradually and reaches its maximum value in the 3rd and 4th story levels. The maximum values in NSSI-2, SSI-4, SSI-5 and SSI-6 using ESL method are 0.00115, 0.00134, 0.0015 and 0.00176, respectively. The maximum values in NSSI-2, SSI-4, SSI-5 and SSI-6 using response spectra (RS) method are 0.00104, 0.00172, 0.00189 and 0.00218, respectively. The average values of using time history method of nine earthquake ground motion records are 0.00106, 0.00111, 0.00115 and 0.00117, respectively. As the soil stiffness decreases; the story drift ratio increases. The story drift values calculated by TH method have higher values than ESL and RS methods, while those obtained by RS have lower values for story drift.

Figure 7a, b and c shows the story drift ratio response distribution over building height compared to that response value of fixed-base model for 12-story model. The story drift ratio increases over the building height as the supporting soil changes from stiff to soft condition. This increasing trend is more significant in the upper and lower
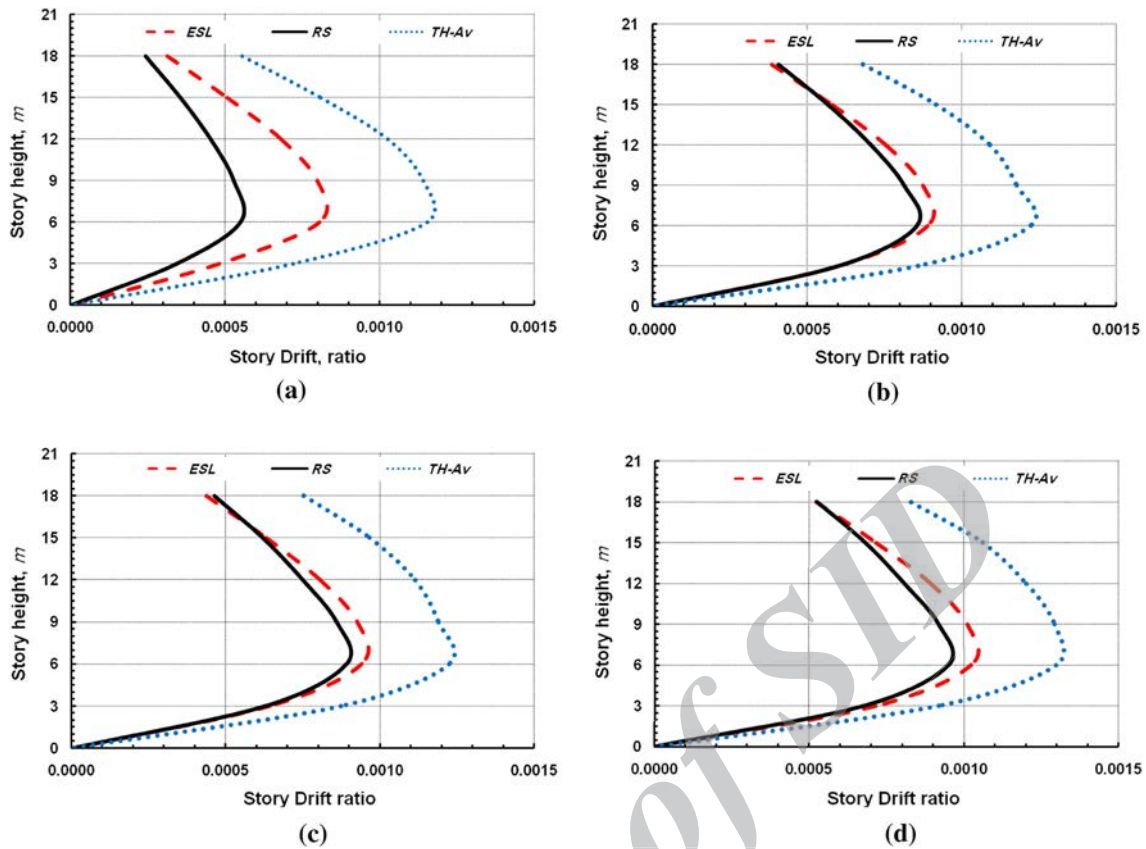
Fig. 4 Story drift ratio of 6-story models. **a** NSSI-1, **b** SSI-1, **c** SSI-2 and **d** SSI-3
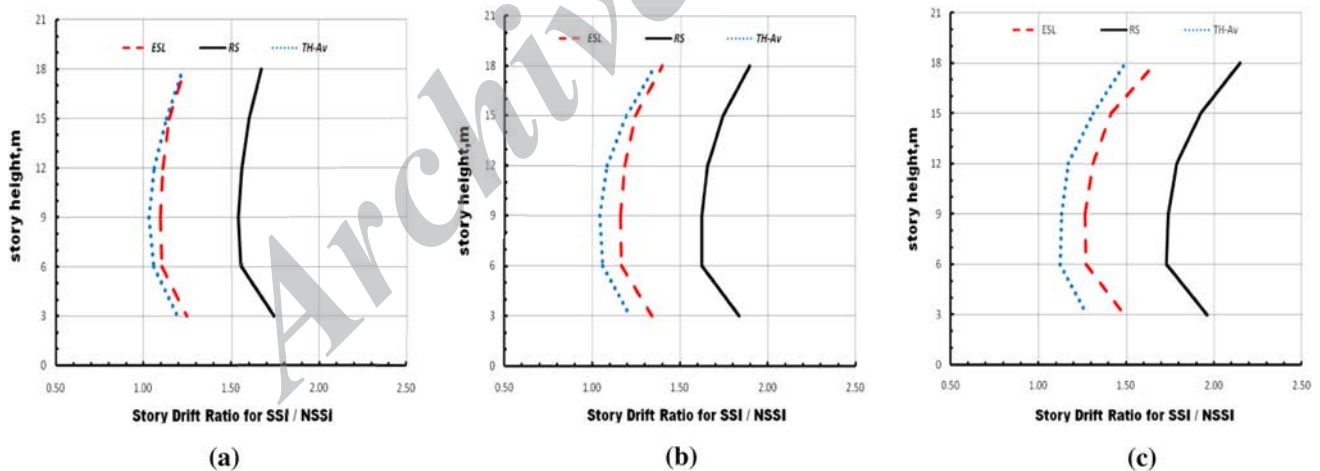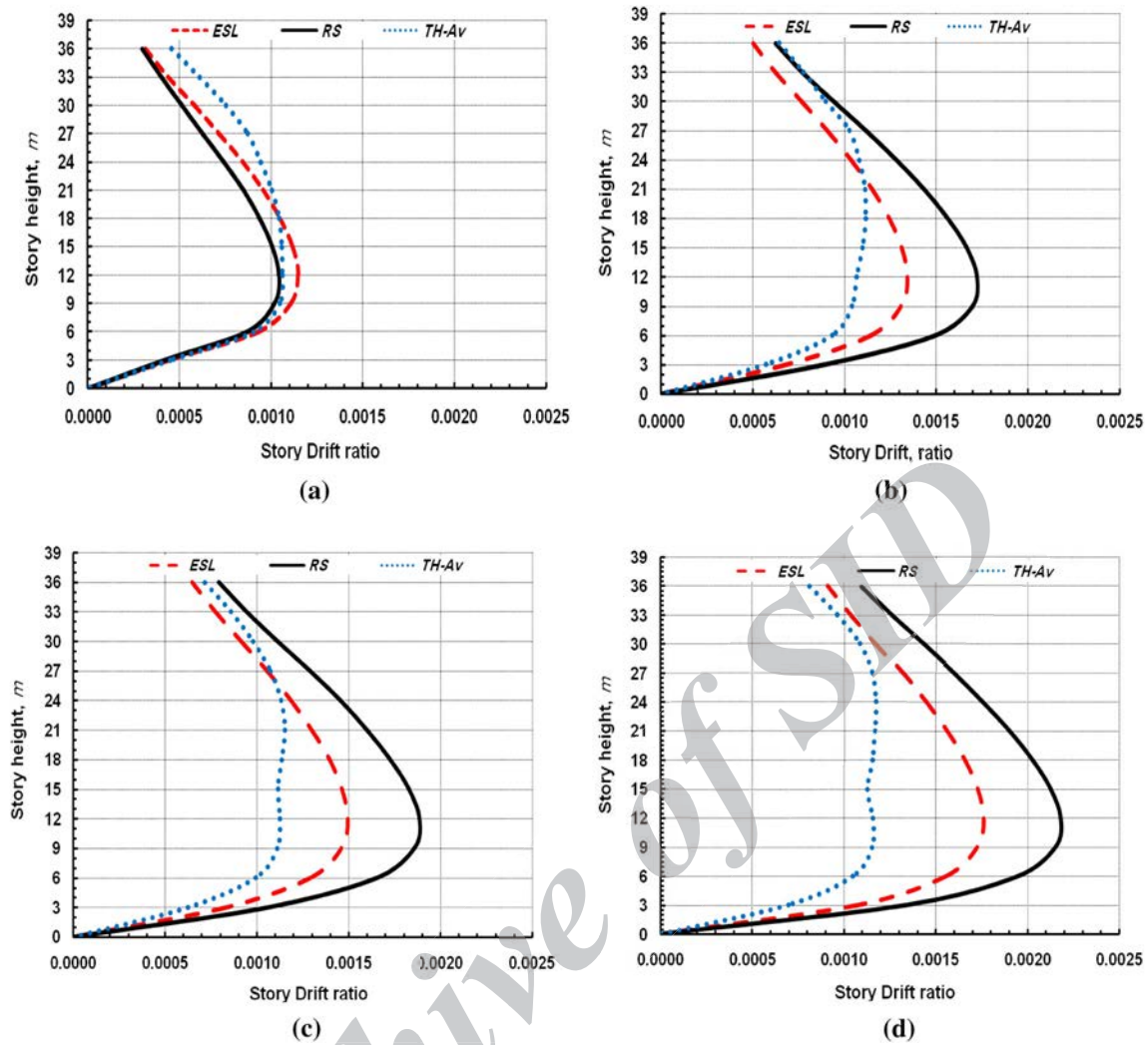

Fig. 5 Story drift ratio of SSI model to that of NSSI model of 6-story models. **a** SSI-1, **b** SSI-2 and **c** SSI-3

stories. The maximum response ratios of SSI-4, SSI-5 and SSI-6 compared to those of fixed base using ESL method are 1.59, 2.06 and 2.89, respectively. The maximum response ratios of SSI-4, SSI-5 and SSI-6 compared to those of fixed base using response spectra method (RS) are 2.09, 2.65 and 3.68, respectively. The average values of using time history method (TH-Av) of nine earthquake

ground motion records are 1.4, 1.56 and 1.76, respectively. As the soil stiffness decreases, the story drifts ratio response ratio increases. Lower and upper stories are more affected with SSI than middle stories. As the raft foundation underneath soil flexibly causes the increase of story drift ratio. The greatest story drift ratio increase occurs for the structures located on the soft soil. The SSI gets more

Fig. 6 Story drift ratio of 12-story models. **a** NSSI-2, **b** SSI-4, **c** SSI-5 and **d** SSI-6
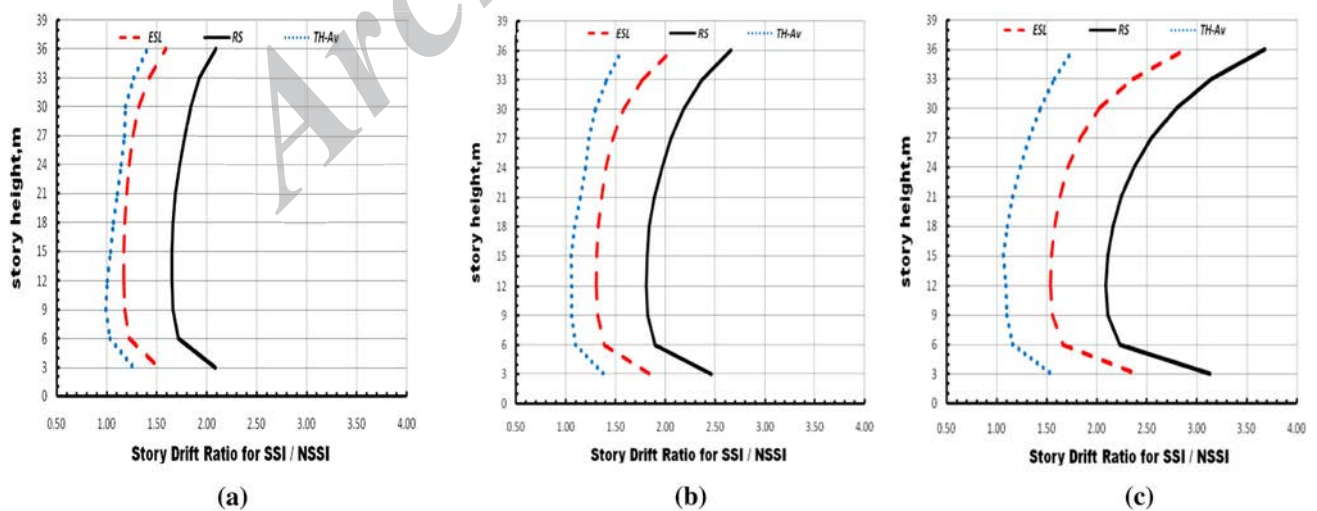

Fig. 7 Story drift ratio of SSI model to that of NSSI model of 12-story models. **a** SSI-4, **b** SSI-5 and **c** SSI-6

significant effect on story drift ratio as the number of story increases.

Story lateral displacement response

Soil–structure interaction particularly for MRF buildings resting on relatively soft soils may significantly amplify the lateral displacements and inter-story drifts. This amplification of lateral deformations may change the performance level of the building frames. Thus, a comprehensive dynamic analysis to evaluate the realistic performance level of a structure should consider the effects of SSI in the model. In this study, an enhanced numerical soil–structure model has been developed which treats the behavior of soil and structure with equal rigor. In this study, the effect of SSI on the story lateral displacement of 6-story and 12-story buildings has been studied using three different analysis methods. The lateral displacement profile is presented in Figs. 8, 9, 10 and 11. It is observed that the displacement increase occurs in SSI models, the displacement increases more in foundations located on soft soil and this value decreases with increasing soil rigidity.

Figure 8a, b, c and d shows that story displacement profile over building height of 6-story increases nonlinearly with the structural height. The maximum displacement response demands for NSSI-1, SSI-1, SSI-2 and SSI-3 models reach: using equivalent static load method 9.8, 11.5, 12.6 and 14.5 mm respectively; using response spectra method 5.9, 9.5, 10.6 and 12.4 mm respectively and using time history method (average value of nine earthquake records) 14.11, 15.62, 15.8 and 18.1 mm respectively. As the soil stiffness decreases, the story displacement increases. Story displacement from TH analysis is higher than ESL and RS analysis.

Figure 9a, b and c shows that story displacement response ratio distributions of 6-story SSI models uniformly increase over all stories. The rate of increase becomes higher for the 1st and 2nd stories. The maximum response ratios of SSI-1, SSI-2 and SSI-3 using ESL method are 1.46, 1.69 and 2.15, respectively. The maximum response ratios of SSI-1, SSI-2 and SSI-3 using response spectra method are 1.88, 2.22 and 3.0, respectively, and the average values of using time history method of nine earthquake ground motion records are 1.42, 1.59 and 1.92, respectively. Lower stories are more affected with SSI than the rest stories.

Figure 10a, b, c and d shows that story displacement profile over building height of 12-story increases nonlinearly with the structural height. The maximum displacement response demands for NSSI-2, SSI-4, SSI-5 and SSI-6 models reach: using equivalent static load method 26.5, 33.9, 39.6 and 49.6 mm respectively; using response spectra method 21.6, 39.4, 46.3 and 58.5 mm respectively and using time history method (average value of nine earthquake records) 26.1, 27.5, 28.0 and 30.7 mm respectively. As the soil stiffness decreases, the story displacement increases. Story displacement from TH analysis is higher than ESL and RS analysis.

Figure 11a, b and c shows that story displacement response ratio distributions of 12-story SSI models uniformly increase over all stories. The rate of increase becomes higher for the 1st and 2nd stories. The maximum response ratios of SSI-4, SSI-5 and SSI-6 using ESL method are 1.83, 2.5 and 3.7, respectively. The maximum response ratios of SSI-4, SSI-5 and SSI-6 using response spectra method are 2.7, 3.7 and 5.4, respectively, and the average values of using time history method of nine earthquake ground motion records are 1.47, 2.0 and 2.74, respectively. Lower stories are more affected with SSI than the other stories. SSI, particularly for MRF buildings with raft foundation resting on relatively soft soils, creates large lateral displacements and inter-story drifts which may change the performance level of the buildings.

Story shear force response

This investigation is aimed to better understand the seismic performance of typical MRF buildings incorporating soil–structure effect. The seismic response of the structure in terms of the story shear as well as internal forces over the height of the structural elements is selected as response parameters of interest as these are generally considered the most important response parameters in seismic design practice. The effect of SSI on the story shear response profile over height for 6- and 12-story buildings has been calculated using the three different analysis methods and compared to that obtained from fixed-base model. The effect variation of change in story shear due to the incorporation of soil flexibility as compared to the same obtained at fixed-base condition expressed as a ratio of such response of SSI models to that of fixed-base model has been plotted in Figs. 12, 13, 14 and 15.

Figure 12a, b, c and d shows the story shear response profile over building height of 6-story models. The maximum base shear values for NSSI-1, SSI-1, SSI-2 and SSI-3 models using ESL method are constant value of 121.64 t. Using response spectra method, the maximum base shear values for NSSI-1, SSI-1, SSI-2 and SSI-3 models are 82.5, 116.39, 118.73 and 117.18 t, respectively, and using time history method the average values of nine earthquake ground motion records are 198.62, 190.78, 180.12 and 178.57 t, respectively. For RS analysis, as the soil spring stiffness decreases, the story shears increase. For ESL analysis, story shear is not sensitive to the foundation–soil flexibility. For TH analysis, as the soil spring gets softer, the story shears decrease. Story shear from TH analysis is higher than ESL and RS analysis.
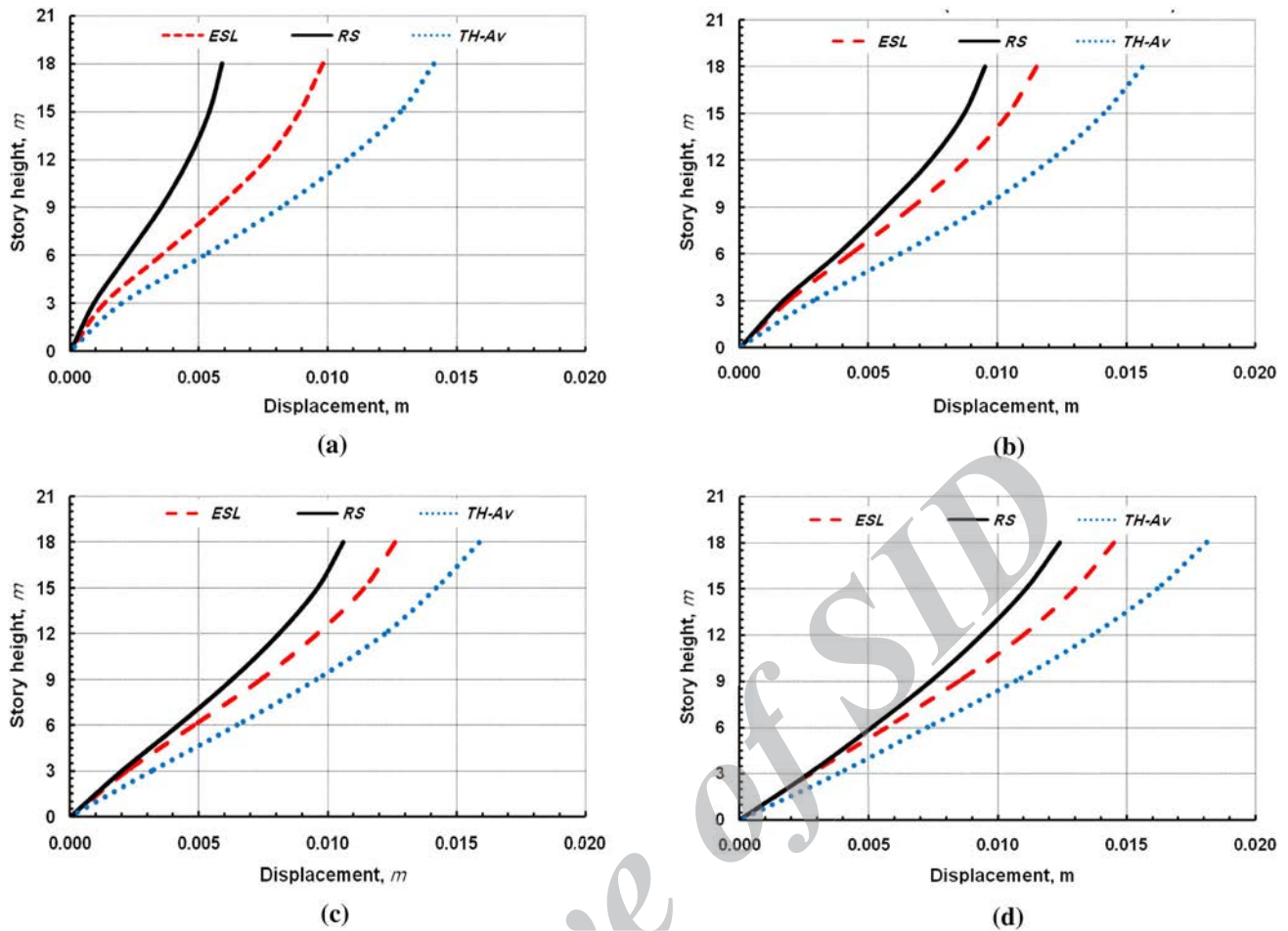
Fig. 8 Story lateral displacements of 6-story models. **a** NSSI-1, **b** SSI-1, **c** SSI-2 and **d** SSI-3
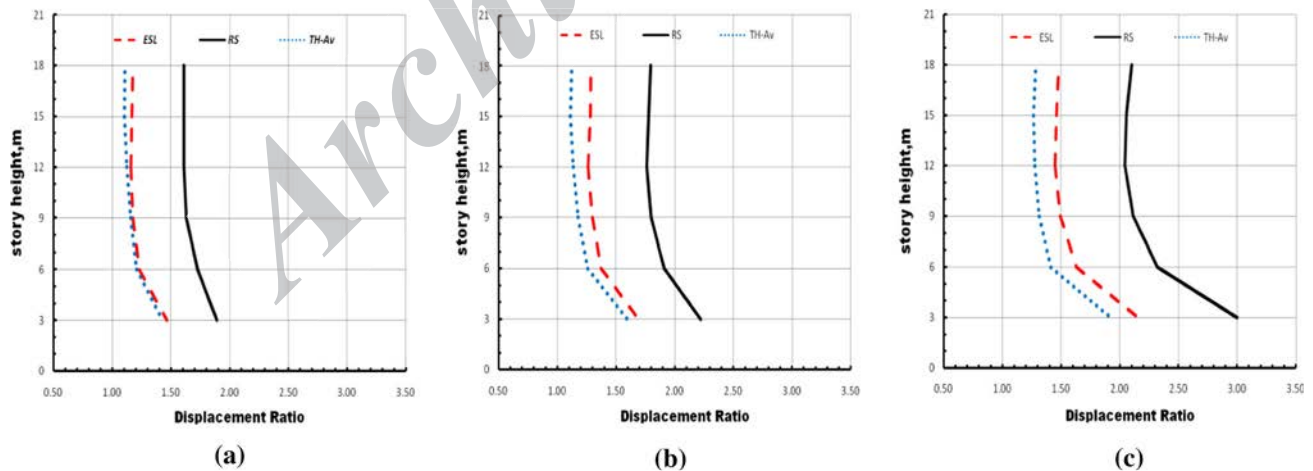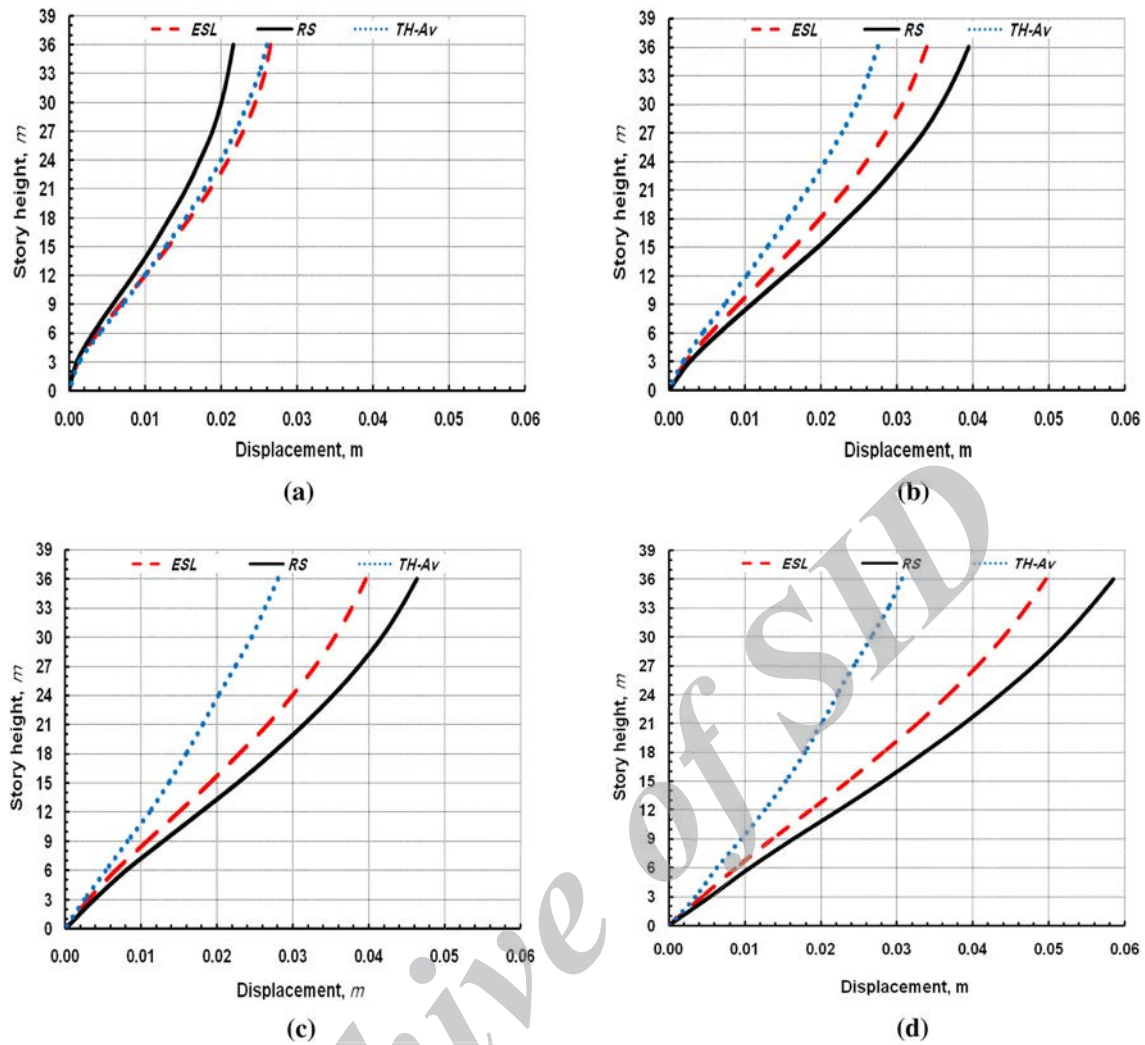

Fig. 9 Story lateral displacement of SSI model to that of NSSI model of 6-story models. **a** SSI-1, **b** SSI-2 and **c** SSI-3

Figure 13a, b and c shows story shear response ratio of SSI models compared to that of fixed-base model of 6-story buildings. Response ratio of story shear under ESL analysis is equal to one for all models. The maximum response ratios of SSI-1, SSI-2 and SSI-3 using response spectra method are 1.53, 1.56 and 1.44, respectively, and using time history method; the average values of nine earthquake ground motion records are 1.08, 1.09 and 0.9, respectively.

Fig. 10 Story lateral displacements of 12-story models. **a** NSSI-2, **b** SSI-4, **c** SSI-5 and **d** SSI-6
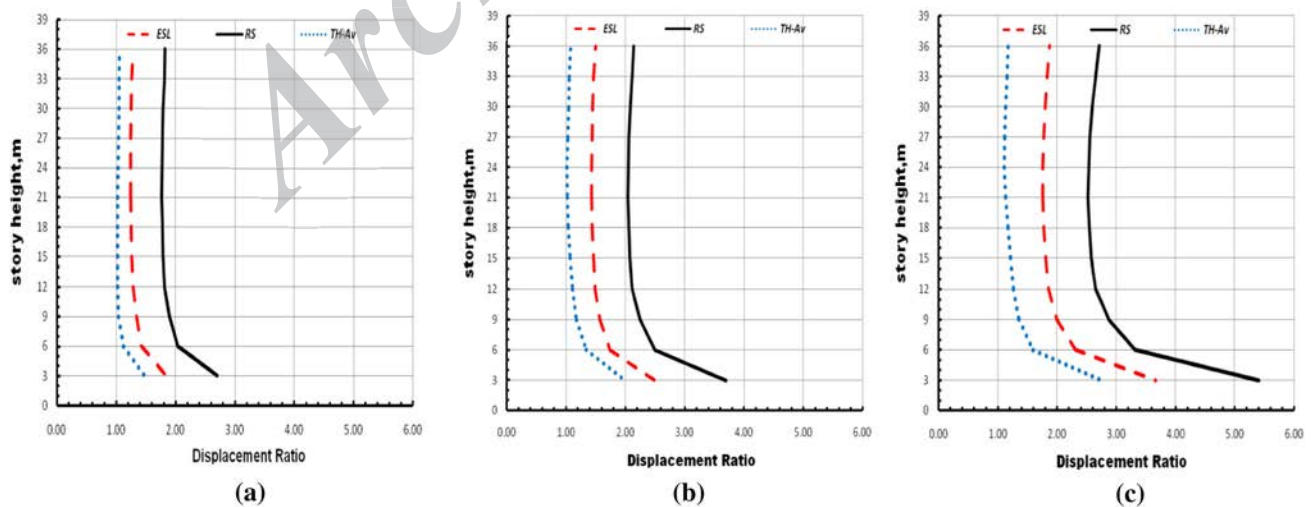

Fig. 11 Story lateral displacement of SSI model to that of NSSI model of 12-story models. **a** SSI-4, **b** SSI-5 and **c** SSI-6
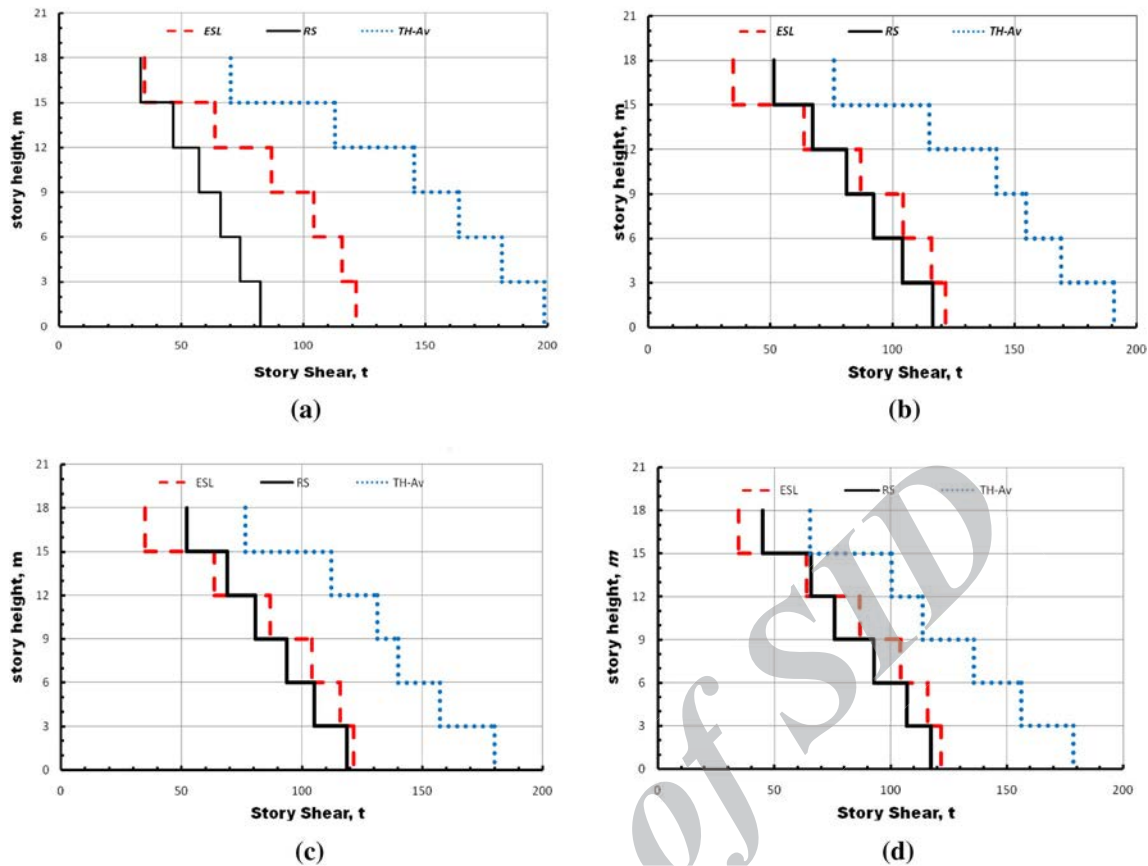
Fig. 12 Story shear force response of 6-story models. **a** NSSI-1, **b** SSI-1, **c** SSI-2 and **d** SSI-3
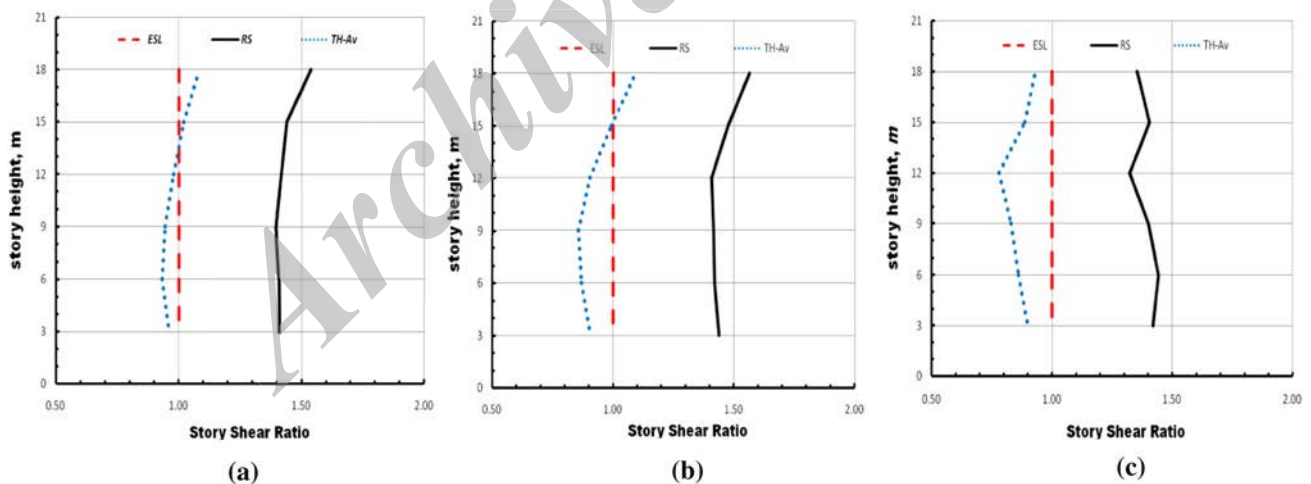

Fig. 13 Story shear force response of SSI model to that of NSSI model of 6-story models. **a** SSI-1, **b** SSI-2 and **c** SSI-3

Figure 14a, b, c and d shows the story shear response profile over building height of 12-story models. The maximum base shear values for NSSI-2, SSI-4, SSI-5 and SSI-6 models using ESL method are constant value of 186.24 t. Using response spectra method, the maximum base shear values for NSSI-2, SSI-4, SSI-5 and SSI-6 models are 163.9, 233.34, 233.81 and 234.93 t, respectively, and using time history method the average values of nine earthquake ground motion records are 211.5, 209.46, 196.92 and 185.41 t, respectively. For RS analysis, as the soil spring stiffness decreases, the story shears increase. For ESL analysis, story shear is not sensitive to the foundation soil
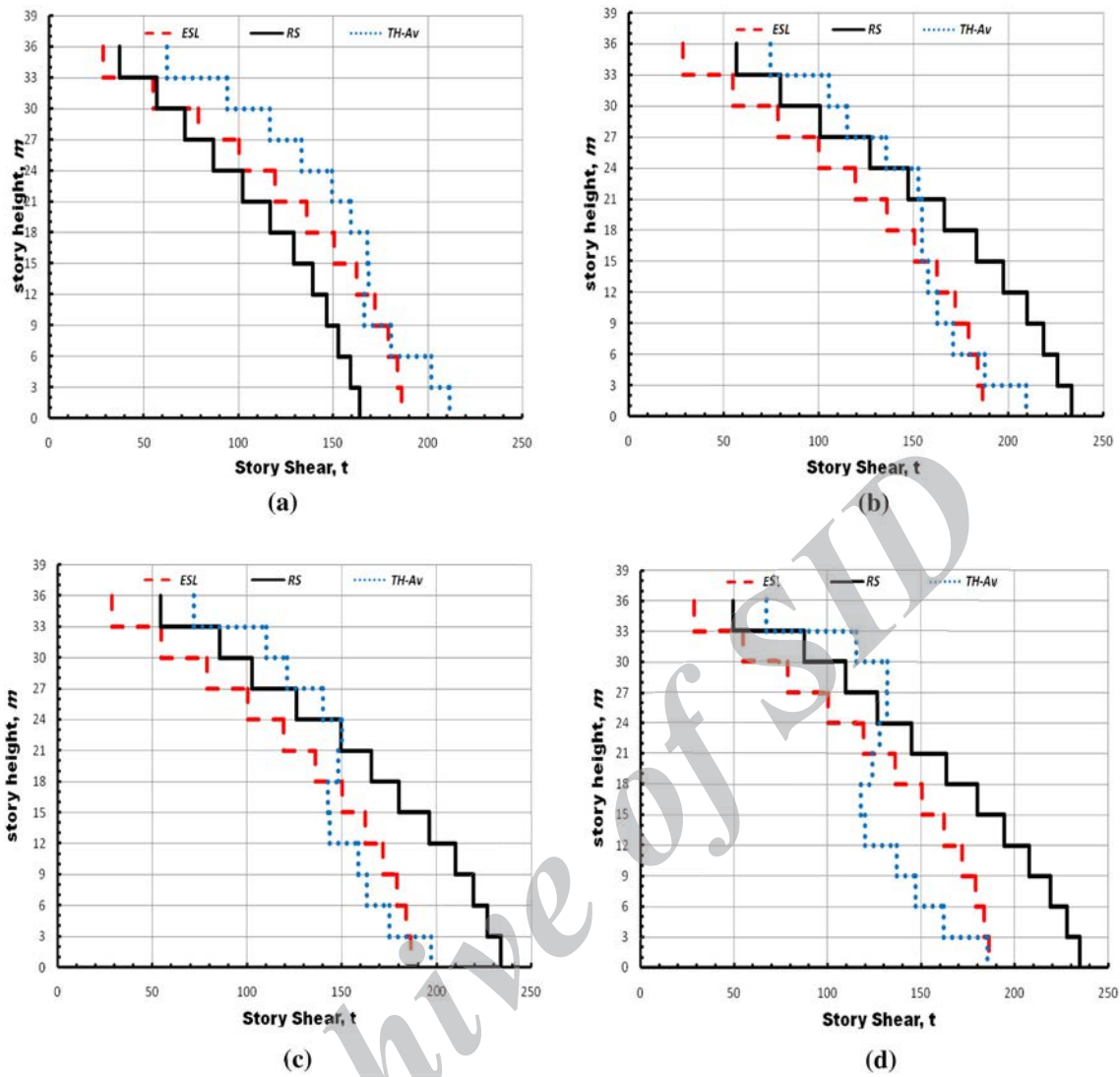
Fig. 14 Story shear force response of 12-story models. a NSSI-2, **b** SSI-4, **c** SSI-5 and **d** SSI-6
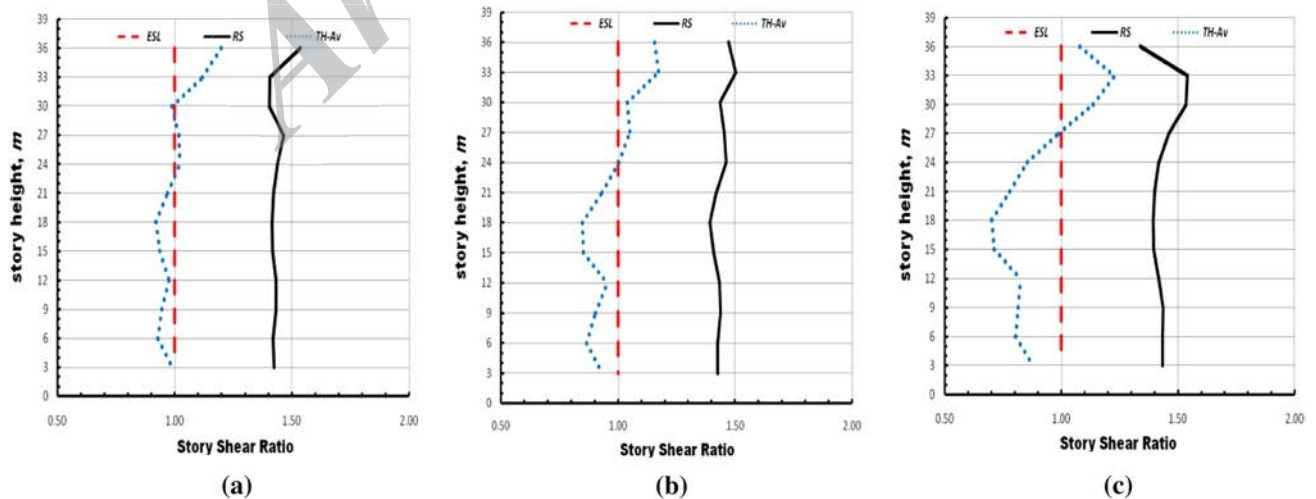

Fig. 15 Story shear force response of SSI model to that of NSSI model of 12-story models. a SSI-4, **b** SSI-5 and **c** SSI-6

flexibility. For TH analysis, as the soil spring gets softer, the story shears decrease. Story shear from TH analysis is higher than ESL and RS analysis.

Figure 15a, b and c shows story shear response ratio of SSI models compared to that of fixed-base model of 12-story buildings. Response ratio of story shear under ESL analysis is equal to one for all models. The maximum response ratios of SSI-4, SSI-5 and SSI-6 using response spectra method are 1.53, 1.50 and 1.54, respectively, and using time history method; the average values of nine earthquake records are 1.2, 1.17 and 1.23, respectively.

Summary and conclusions

The study as a whole may prove useful in formulating design guidelines for seismic design of building frames incorporating the effect of soil flexibility. In this study, the effects of seismic SSI are analyzed for typical multi-story building resting on raft foundation. The influences of parameters of slab-column structure-raft foundation–soil model of a practical engineering are carried using three methods of analysis: time history analysis with a suite of nine time history records, the ESL and the response spectrum methods, which adopted in the Egyptian code for load and forces (ECP-201; 2008). A mathematical model of the complete building–foundation–soil system is developed to determine response quantities not directly available from the records and to ascertain the effects of interaction. The model is calibrated using the dynamic properties of the building as determined from the processed records. The evaluation of SSI is performed through comparison with the results obtained with those from fixed base assumption. The main findings of the study are summarized as follows:

For all models (NSSI and SSI models), The empirical expression for calculating the fundamental period of vibration by ECP-201 (2008) underestimates the fundamental period compared to that models. The structural model is larger than the fundamental period calculated from the ECP-201 (2008) empirical expression. As the soil spring stiffness increases, the fundamental period for the structural model decreases. This means that the fundamental period is not only a function of building height but also a function of SSI. The fundamental period calculated from the SSI models is larger than that from NSSI models (fixed-base models), meaning that the change in soil stiffness could have significant effect on the fundamental period of vibration. The soil foundation flexibility change affects the seismic demands on the whole structure. SSI model with soft soil condition displays higher story displacement response demands compared to that of fixed base model (rigid foundation/stiff soil assumptions). The SSI effects are amplified as the number of stories increases. The code empirical methods underestimate the

fundamental natural period of structures with SSI. This effect on period calculation means that the design forces are likely to be overestimated, which is conservative.

The story shear response calculated from ESL method is independent of SSI effects and depends only on the building weight. On the contrary, the story shear responses calculated from RS and TH methods are highly dependant on the foundation and underneath soil stiffness. Story drift response ratio increases as the soil stiffness deceases. Story drift response ratio increases with the increasing number of stories. Lower and upper stories are more affected with SSI than the middle stories. This effect is amplified as the soil stiffness decreases. The story displacement response increases as the soil stiffness decreases. Story displacement response ratio increases with the increasing number of stories. Lower stories displacements are more affected with SSI than the rest stories.

The model is then used to evaluate the effects of SSI on the maximum base shear force, overturning moment and displacement for the MRF multi-story buildings. The analysis demonstrates that SSI has a significant effect on the base forces and roof displacement of the building compared to the typical assumption in which interaction would be neglected. When the ground is stiff enough, the dynamic response of the structure will not be influenced significantly by the soil properties during the earthquake, and the structure can be analyzed under the fixed base condition. When the structure is resting on a flexible medium, the dynamic response of the structure will be different from the fixed base condition owing to the interaction between the soil and the structure. It is concluded that the dynamic SSI plays a considerable role in seismic behavior of mid-rise building frames including substantial increase in the lateral deflections and inter-story drifts and changing the performance level of the structures. Thus, considering SSI effects in the seismic design of mid-rise moment-resisting building frames, particularly when resting on soft soil deposit, is essential. If SSI is not taken into account in analysis and design properly; the accuracy in assessing the structural safety, facing earthquakes, could not be reliable. The conventional design procedures excluding SSI may not be adequate to guarantee the structural safety of regular mid-rise moment- resisting building frames resting on soft soil deposits.

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