CAPITAL UNIVERSITY OF SCIENCE AND TECHNOLOGY, ISLAMABAD

Identification of an Efficient Method for Practicing Designers to Incorporate Soil-Structure Interaction Effects

by

Muhammad Waqas

A research project submitted in partial fulfillment for the degree of Master of Science

in the

Faculty of Engineering
Department of Civil Engineering

2018

This effort is devoted to my respected parents, who helped me through each troublesome of my life and yielded every one of the comforts of their lives for my brilliant future. This is likewise a tribute to my best teachers who guided me to go up against the troubles of presence with ingenuity and boldness, and who made me what I am today.

CAPITAL UNIVERSITY OF SCIENCE & TECHNOLOGY
ISLAMABAD

CERTIFICATE OF APPROVAL

Identification of an Efficient Method for Practicing Designers to Incorporate Soil-Structure Interaction Effects

by

Muhammad Waqas

(MCE153024)

RESEARCH PROJECT EXAMINING COMMITTEE

S. No.	Evaluator	Name	Organization
(a)	Examiner	Engr. Dr. Munir Ahmed	CUST, Islamabad
(b)	Supervisor	Engr. Dr. Majid Ali	CUST, Islamabad

Engr. Dr. Majid Ali
Research Project Supervisor
April, 2018

Engr. Dr. Ishtiaq Hassan
Head
Dept. of Civil Engineering
April, 2018

Dr. Imtiaz Ahmed Taj
Dean
Faculty of Engineering
April, 2018

Author's Declaration

I, **Muhammad Waqas** hereby state that my MS project titled "**Identification of an Efficient Method for Practicing Designers to Incorporate Soil-Structure Interaction Effects**" is my own work and has not been submitted previously by me for taking any degree from Capital University of Science and Technology, Islamabad or anywhere else in the country/abroad.

At any time if my statement is found to be incorrect even after my graduation, the University has the right to withdraw my MS Degree.

(Muhammad Waqas)

Registration No: MCE153024

Plagiarism Undertaking

I solemnly declare that research work presented in this project titled "**Identification of an Efficient Method for Practicing Designers to Incorporate Soil-Structure Interaction Effects**" is solely my research work with no significant contribution from any other person. Small contribution/help wherever taken has been dully acknowledged and that complete project report has been written by me.

I understand the zero tolerance policy of the HEC and Capital University of Science and Technology towards plagiarism. Therefore, I as an author of the above titled project declare that no portion of my project has been plagiarized and any material used as reference is properly referred/cited.

I undertake that if I am found guilty of any formal plagiarism in the above titled project even after award of MS Degree, the University reserves the right to withdraw/revoke my MS degree and that HEC and the University have the right to publish my name on the HEC/University website on which names of students are placed who submitted plagiarized work.

(Muhammad Waqas)

Registration No: MCE153024

List of Publications

It is certified that following publication(s) has been made out of the research work that has been carried out for this project:-

Conference Proceedings

1. Waqas M. and Ali M. (2018). An efficient approach to incorporate soil-structure interaction effects for practicing engineers. *Annual Canadian Society for Civil Engineering Conference*, Fredericton NB, June 13-16.

   (Abstract submitted and paper ready for submission).

(Muhammad Waqas)

Registration No: MCE153024

Acknowledgements

- Wealthiest thanks to Almighty Allah for a tremendous measure of vitality, power and the miraculous pushes occurring in a sweetly coordinated manner, only a few to mention, which drive our lives.

- I need to express my sincere thanks to Associate Professor Engr. Dr. Majid Ali under whose direction the research was led. His direction was precious at each progression of this work. His outstanding showing aptitudes helped me get a handle on the topic rapidly. His collaboration at every single phase of my basic choices at Capital University has been significant.

- I would thank Engr. Tariq Mahmood for his sincere cooperation to complete this research project.

Abstract

The soil-structure interaction (SSI) influences the many aspect of structure i.e. cost, safety and serviceability. Therefore, it plays an important role in substantial development of any country where the devastating earthquakes have occurred repeatedly. SSI techniques have been come out as powerful methods to incorporate multiple degrees of freedom. Building structures can accommodate more degree of freedom due to the support flexibility, and therefore different dynamic characteristics than the rigidly mounted structures. But, the concerns of practitioners are paved in hectic efforts to incorporate SSI. Practicing engineers are facing many challenges to implement SSI practice due to difficult literature and time consumption. Therefore, the overall aim of this research program is to incorporate SSI practice in analysis and design of building structures. The goal of this study is to investigate through literature research; the performances based assessment of SSI effects and identify an efficient method for practicing designers to incorporate SSI in analysis and design of structures. In this regard, the documentation of development regarding SSI, preferably, in last five years was carried out to come up with an efficient approach which designers can easily adopt in their practice. It is concluded that N2-SSI is an efficient and easy to adopt SSI method in which the soil effect is introduced on the non-linear response of structure. This work will increase the awareness of SSI effects and convince practicing designers to incorporate SSI in their analysis and design of structures.

Contents

List of Figures

List of Tables

Abbreviations

ATC	Applied technology council
ADRS	Acceleration displacement response spectrum
BEM	Boundary element method
CSM	Capacity spectrum method
DCM	Displacement coefficient method
DBD	Displacement-based design
ESDOF	Equivalent Single degree of freedom
FEMA	Federal emergency management agency
FBD	Force-based design
FEM	Finite element method
MDOF	Multiple degree of freedom
NEHRP	National earthquake hazards reduction programme
NSP	Nonlinear static procedure
NRHA	Non-linear response history analysis
SSI	Soil-structure interaction
SDOF	Single degree of freedom

Chapter 1

Introduction

1.1 Prelude

A 7.6 Richter scale earthquake caused havoc in Pakistan. Moderate to severe damage was noticed in masonry and RC buildings even hundreds of kilometers away from epicenter. Fatahi et al. (2011) proposed that traditional design approach without SSI was insufficient for building structures. Thus, earthquake preparedness followed by adequate strengthening strategies for building structures were needed to be addressed, Dutta et al. (2016). But the poor understanding of fundamental SSI principles is the major concern for design engineers to deploy the practical applications of SSI for building structures. Hectic efforts to understand the literature and limited guidance to codes and standards made obstruct this practice, NEHRP, (2012).

Performance based seismic design addresses multiple performance objectives at the associated earthquake hazard levels, Zameeruddin et al. (2016). SSI accommodates more degree of freedom to structure due to the support flexibility. It is more efficient to treat soil as rigid base for stiff soil overlain by soft structures. However, SSI becomes very important for a case of stiff structures on soft soil . It reduces the structural demand(s) by accounting rocking, sliding, torsion etc.

In the later case, SSI tends to enhance natural period as well as damping of the structure, Veletsos et al. (1974); Kramer, (1996).

Application of SSI puts an imperative part in substantial development, especially in countries where earthquakes happen frequently, and where site specific response analysis of ground motion are required to be established on real scale design, Mahmood et al. (2016). Close collaboration between structural and geotechnical engineers is an important issue for the performance base implementation in structural design. In this study, documentation of recent developments regarding SSI has been done through literature research. Simplified and an efficient approach has been identified which designers can easily adopt in their practice.

1.2 Research Motivation and Problem Statement

Academia's and officials are trying to produce efficient and user friendly tools to incorporate SSI. But the concern of practitioners on incorporating SSI is paved in hectic efforts to incorporate SSI. Designers would prefer an efficient and easy to adopt approach to incorporate SSI for analysis and design of structures. Thus, the problem statement is as follows:

"An efficient approach is required to deploy SSI practice in analysis and design of building structures. Practicing engineers are facing many challenges to implement SSI practice into design. This exercise is hampered by difficult literature and time consumption. Recent research developments on different approaches are needed to be studied. An efficient approach will make a way easy to adopt SSI practice in analysis and design of building structures".

1.3 Overall/Specific Research Aims and Scope of Work

The overall aim of the research project is to incorporate SSI in analysis and design of structures.

The specific aim of this MS work is to investigate, through literature research, the performance based assessment of SSI effects and to identify an efficient method for practicing designers to incorporate SSI in analysis and design of structures.

This particular objective is accomplished by the following tasks (defining the scope of present research project work):

i. The scope of the work includes the documentation of development regarding SSI in last five years to come up with an efficient approach through literature research, which designers can easily adopt in their practice.

ii. Validation of this proposed efficient method is outside the scope of this MS research project work.

1.4 Investigation Methodology

In this numerical study, identification of structures having adverse effects of neglecting SSI aspects was carried out. Literature research of, preferably, last five years (2012-2017) was acquired to study of different approaches to incorporate SSI in analysis and design of structures. An efficient and easy to adopt approach has been identified to make SSI practice easy for practicing designers to incorporate effects of SSI in their analysis and design of structures.

1.5 Project Outline

The Research Project contains four chapters. These are:

Chapter 1 includes of introduction. It explains the damage due to neglecting SSI in practice, research motivation and problem statement, overall goal and specific research aims, scope of work, investigation methodology and project outline.

Chapter 2 contains the literature review. It comprises of background, damage in structures due to ignoring SSI, various techniques covering direct and indirect analysis methods to incorporate SSI effects for design and analysis of building structures, data required for SSI effects, various soil modeling methods and approaches in SSI analysis, simplified SSI technique identified and summary of chapter 2.

Chapter 3 incorporates the discussion. It consists of background, identification of an efficient method to incorporate SSI effects and limitations of structure analysis and design in current practice. Conventional adopted procedure and recommendations by practicing designers, step-wise procedure to incorporate SSI effects in analysis and design of structures, formulation of N2-SSI model, values of soil springs and dashpots, its application has been discussed and summary of chapter 3.

Chapter 4 summarizes the whole work. It comprises of conclusions and recommendations for future needs.

Consecutive to the end of chapter 4, all the references are given.

At the end of this report, Annexure introduces some softwares /tools which were used to develop numerical models of soil-foundation-structure interaction.

Chapter 2

Literature Review

2.1 Background

A seismic SSI considers the cumulative response of structure with the supporting soil. To execute SSI in practice, an understanding of practical phenomenon and effective methodology for simulating its effects are required. Analysis procedures in FEMA-356, ATC-40, ASCE-41 and EC-8 not completely address the flexible foundation effects. The decrease in seismic demand of structures with respect to ground motion are not sufficiently described in these procedures, Stewart et al. (2004) .

Simplified linear and non-linear static analysis procedure and guidance to incorporate SSI effects has been given in this chapter. In view of the latest research developments, efficient SSI techniques are identified to execute this practice in analysis and design of structures.

2.2 Damage in Structures due to Ignoring SSI

Cracks at various locations of RC frame structure (Ground + three storey) located far away from epicenter has been shown in Fig. 2.1. These type of damages concluded that earthquake preparedness and adequate strengthening strategies for building structures are needed to be resolved.

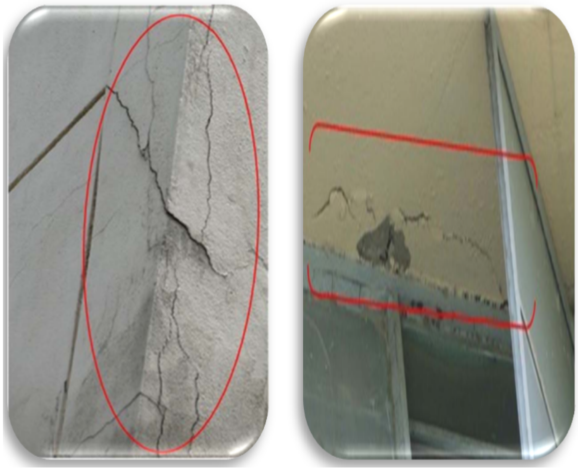

FIGURE 2.1: Cracks located at different locations of the building due to earthquake, Dutta et al. (2016).

Earthquake shaking may incite sloshing effect in water retaining structures, which may not be withstood by the supporting structures during earthquake. Infact, some of the observers revealed about very heavy shaking exhibited by the elevated water tanks during earthquake. The columns supporting the water tank are deteriorated at couple of areas (Fig. 2.2) exposing the reinforcement to the atmosphere and overall the health of the water tank structure was not sufficient enough, Dutta et al. (2016).

FIGURE 2.2: Cracks located at rectangular OHWT, Dutta et al. (2016).

2.3 Techniques to Incorporate SSI Effects

SSI accommodates more degree of freedom to structure due to support flexibility. It lessens the seismic demand of structure by taking into account rocking, sliding, torsion etc. Every mode of these motions eats up energy from earthquake and can serve to enhance damping in the system and reduce the anticipated damage.

SSI has almost no impact for soft structure on firm soil. However, for a case of a stiff structure on soft soil, SSI becomes very important. For latter case, SSI has a tendency to lengthen the natural period and damping of the building. Therefore, SSI is the function of following:

i. Structure stiffness with respect to soil firmness.

ii. Structure slenderness with respect to foundation width and,

iii. Mass of the structure with respect to mass of the soil supporting foundation.

The flowchart in Fig. 2.3 shows systematically, the techniques to incorporate SSI in performance based design. These are linear and non-linear analysis techniques. In these techniques, SSI can be incorporated either by direct or indirect approach. In this study, non-linear static analysis procedure has been followed to identify simplified but efficient method to incorporate SSI by indirect approach.

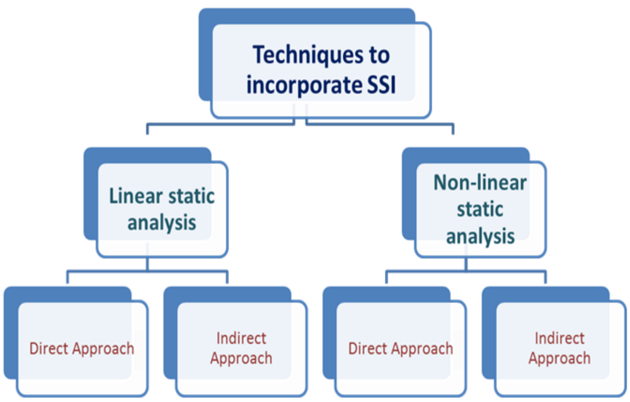

FIGURE 2.3: Techniques to incorporate SSI in PBD.

The choice of analysis type is mainly relies upon the hazard level and type of structure.

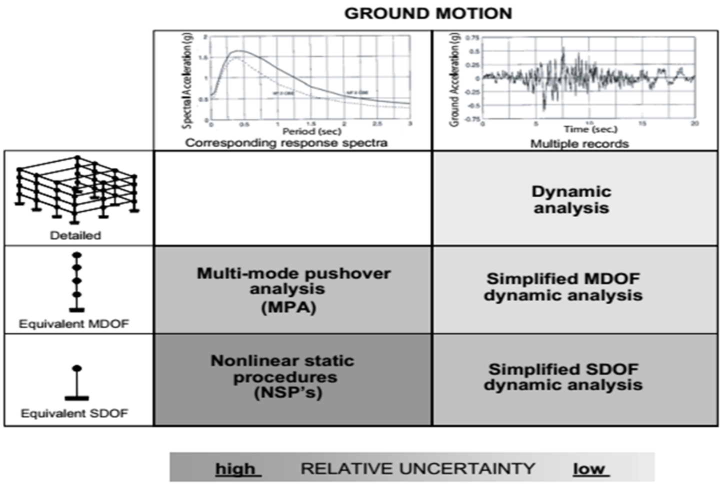

FIGURE 2.4: Non-linear seismic analysis methods, FEEMA-440, (2005).

Figure 2.4 shows the matrix depicting possible inelastic seismic analysis procedures and ground motion characteristics along with trend of uncertainties in the results. There are two general ways to incorporate SSI effects.

2.3.1 Direct SSI Analysis Methods

Direct SSI analysis, as depicted in Fig. 2.5, use numerical models, i.e. finite element model for representation of soil along with structural and foundation elements.

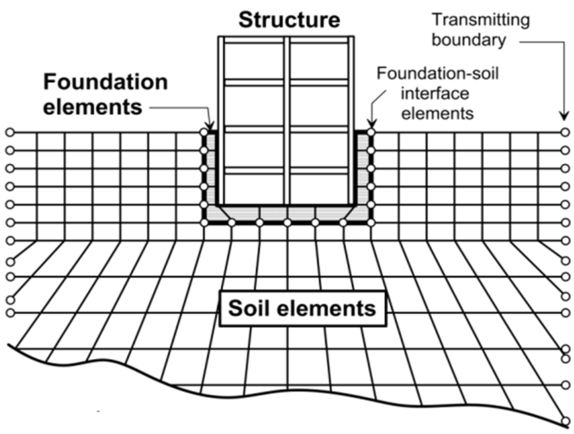

FIGURE 2.5: Systematic illustration of a direct analysis of SSI, NEHRP (2012).

2.3.2 Indirect SSI Analysis Methods

Indirect SSI analysis approach analyzes kinematic response and inertial response separately, and adds them together to get the total response.

2.3.2.1 Force-based Procedure

These methodologies mainly depend on the forces induced in the structures during seismic excitation. These forces rely on the elastic stiffness of the structure within the elastic stage. During inelastic stage, the conditions come out to be complex. In FBD, strength of the structure should be more than the design loads to keep the structure away from collapse.

The base shear during seismic event by considering SSI effects for force-based design is defined as (SEI/ASCE 7-10):

$$V = C_s W$$

where "C_s" is a seismic coefficient, at building period "T", standardized by the acceleration in percentage of gravity "g", and "W" is the seismic weight of the structure.

SEI/ASCE 7-10 neglects kinematic interaction impacts but provides considerations for inertial interaction impact with respect to enhancing of building period and damping ratio. The time rate in base shear is computed as:

$$\Delta V = \left[C_s - \tilde{C}_s \left(\frac{0.05}{\beta_0} \right)^{.04} \right] W$$

This change in base shear is linked to the change in seismic coefficient. The $\tilde{C}_s$ term presents the seismic coefficient evaluated from the design spectrum at lengthening period $\tilde{T}$. The term $\left(\frac{0.05}{\beta_0}\right)^{.04}$ represents the decrease in spectral ordinate linked with a change in damping from the rigid-base structural damping value of $\beta_i = 0.05$, to the flexible-base value of β_0.

Equation for period lengthening and foundation damping is calculated using equations;

$$\frac{\tilde{T}}{T} = \sqrt{1 + \frac{k}{k_x} + \frac{kh^2}{k_{yy}}}$$

$$\beta_0 = \beta_f + \frac{1}{\left(\tilde{T}/T\right)^n}\beta_i$$

where "k" is the structure stiffness considering single degree of freedom, "k_x" is the horizontal spring stiffness in "x"-direction and "k_{yy}" is the rotational spring stiffness representing the rotation in $x - z$ plane (about the $y - y$ axis) after adding the soil flexibility under rigid foundation. "β_i" is the structure damping in superstructure assuming the fix base, which is 5% for typical structures. "β_f" is the foundation damping, which is a function of soil hysteresis and radiation damping.

2.3.2.2 Displacement-based Procedure

Zameeruddin et al. (2016) reviewed and compared the current practices in performance based seismic evaluation and summarized the displacement based techniques to incorporate SSI in analysis and design of structures.

Unfortunately, the prospective utilization of DBD is not well connected in practice. In DBD, structure response is presented by force vs displacement relationship and computed through pushover analysis. This technique includes the use of static lateral load over the height of the structure. Lagoras et al. (2011) investigated the effect of different static pushover analysis method for seismic design of new structures. The life cycle cost evaluation of seismic performance of structures had been done by CSM, N2 and DCM method.

Modirzadeh et al. (2012) performed earthquake evaluation of RC buildings through pushover analysis and performance goals were obtained through a pushover analysis. Mekki et al. (2016) stated that methodology to incorporate SSI by applying displacement-based procedure involved; hazard analysis, structural/geotechnical analysis, damage analysis, and loss analysis.

2.3.2.2.1 Capacity Spectrum method (ATC-40) The capacity spectrum methodology compares the structure capacity with the demands of seismic ground motion on it. In this method, the procedure to produce a force-deformation relationship (capacity curve) has been developed. This methodology accepts that the equivalent damping of the system is proportional to the area enclosed by the capacity curve. The equivalent period, T_{eq}, is the secant period at which the earthquake ground motion demands, lessens for the equivalent damping, meets the capacity curve. Since damping and the equivalent are both a function of the displacement, the solution to evaluate the maximum inelastic displacement (i.e., performance point) is iterative.

Retrofit and earthquake evaluation of concrete structures highlight the utilization of this method. The method involves determining the target displacement using the following equation:

$$\delta_t = C_0 S_d \left(T_{eq}, \beta_{eq}\right)$$

where coefficient "C_0" is the fundamental mode factor and $S_d(T_{eq}, \beta_{eq})$ is the maximum displacement of linearly elastic SDF system with equivalent time period T_{eq}.

2.3.2.2.2 Displacement coefficient method (ASCE-41) When pushover analysis is implemented, the target displacement, which is the displacement during a given earthquake event of a characteristic node on the top edge of a structure, generally in the roof, is defined with the aid of the formula:

$$d_t = C_0 C_1 C_2 C_3 S_a \frac{T_e^2}{4\pi^2 g}$$

where C_1, C_2, C_3 and C_0 are modification factors, presented in the FEMA-440 guidelines and T_e is the effective fundamental period of the building.

2.3.2.3.3 N2 method (Eurocode-8) This approach utilizes an $R - \mu - T$ relationship rather than highly damped spectra of CSM. "R" and "μ" is response modification factor and ductility ratio of given type of structure and "T" is the natural period of building. The procedure for this method is:

i. Development of the capacity $(V_b - D)$ curve.

ii. From pushover curve of the MDOF system, generate the capacity diagram of an ESDOF system and approximate the capacity curve with an idealized elasto-perfectly plastic relationship to get the period "T_e" of the ESDOF.

iii. The target displacement will be estimated as

$$d^*_{et} = S_a(T_e)\left[\frac{T_e}{2\pi}\right]^2$$

where, $S_a(T_e)$ is the elastic spectra acceleration at the period "T_e". To find the target displacement d^*_t, various expressions are suggested for the short and long range period, thus:

iv. $T < T_C$ (short period range): If $F^*_y = m^* \geq S_a T_e$, the response is elastic and thus $d^*_t = d^*_{et}$ and $d_t = C_0 d^*_t$. On the other way round the nonlinearity and the maximum displacement for ESDOF will be estimated as;

$$d^*_t = \frac{d^*_{et}}{q_u}\left(1 + (q_u - 1)\frac{T_C}{T_e}\right) \geq d^*_{et}$$

where q_u is the ratio of the structural acceleration with unlimited elastic capacity times the modal mass m^* over its yield force, or simply: $q_u = S_a T_e m^* F^*_y$.

v. $T^* > T_C$ (medium and long period range): The target displacement of the inelastic system is equal to that of an elastic structure, thus $d^*_t = d^*_{et}$. The displacement of the MDOF system is always calculated as $d_t = C_0 d^*_t$.

2.3.2.3 Procedures for Including SSI Effects

Inertial interaction relates to displacement and rotation at the foundation level of a structure and come out because of inertial driven forces. However, analysis procedures in FEMA 356, ASCE-41, EC-8 and ATC-40 not completely address the flexible foundation effects. The decrease in seismic demand of structures with respect to ground motion is not sufficiently described in these procedures. Fig. 2.6a and 2.6b depicts the structure and foundation system without SSI and with incorporation of foundation flexibility, respectively.

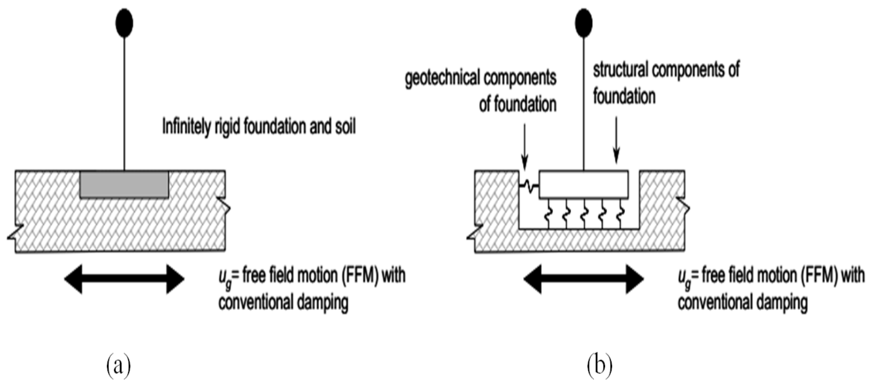

FIGURE 2.6: Foundation modeling assumptions by incorporating SSI, FEMA-440, (2005).

By introducing SSI technique, the anticipated period of the structure increases. The division of forces between different components modifies. The inelasticity order and the modes of inelastic behavior can change, and foundation mechanisms can be directly addressed. These factors resulted in more pragmatic assessment of the performance and anticipated structure behavior.

1. To incorporate kinematic effects, a ratio of response spectra factor will be required to be accounted for the phenomena of;
    i. Base slab averaging and,
    ii. Foundation embedment.
2. The damping due to foundation-soil interaction is related with;
    i. Hysteretic behavior of soil and,

ii. Radiation damping.

Muljati et al. (2015) concluded that DBD method was more effective to incorporate SSI as compared to FBD method. The comparison between FBD and DBD methods has been discussed in Table 2.1. DBD approach showed its efficiency in terms of more explicit understanding of inelastic structures response over a wide range of structural performance level as that of FBD approach.

TABLE 2.1: Comparison between FBDs and DBDs, Muljati et al. (2015), Joy et al. (2016), FEMA 440, (2005).

Equivalent Static FBD	**Non-linear Static DBD**
1- In this method, primary emphasis is on the forces within the structure.	1- This method emphasis on the displacements rather than forces within the structure.
2- It requires several design process repetitions in order to achieve acceptable performance specified by the code.	2- It deliberately designs the structure to achieve a given performance limit state.
3- It can accommodate inelastic response through the application of force reduction factor.	3- It gives more explicit understanding of the inelastic response of a structure to seismic loading.
4- It gives the inelastic response at first yield or near collapse.	4- It gives the inelastic behaviour over a wide range of structural performance level.

2.4 Data Required for SSI Effects

Rayhani et al. (20008) specified the lateral distance of five times for soil boundaries with respect to structure width. Most seismic amplification was taken inside the initial 100 feet of soil profile. That was according to the modern seismic codes. The depth of the bedrock had been assumed at 100 feet. The soil model is comprised of 2D plain strain grid elements. In these elements, the degree of freedom of all points is assumed to be parallel in $x - y$ plane (i.e., in-plane). Tabatabaiefar et al. (2013) and (2014) used viscous boundary conditions at the soil lateral boundaries, known as quite boundaries. The quite boundaries in 2D FEM model are shown in Fig. 2.7. This assumption was taken to avoid reflective waves produced by these boundaries. Viscous dashpots were required at the quite boundaries. The dimensions of footing slab were modeled using a frame element with structural properties similar to the structural model. For initial iterative solutions, shallow footing width had been considered to estimate the moment of inertia.

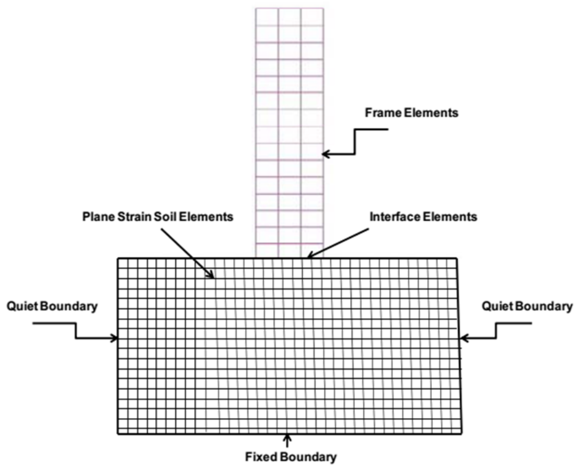

FIGURE 2.7: Components of 2D soil structure model, Tabatabaiefar et al. (2013).

Space for improvement is required to be filled between structural engineers and geotechnical engineers to cooperate with each other on specialized methodologies on projects involving SSI. Given below in Table 2.2, are the details of soil parameters, as an example, required to incorporate SSI in analysis and design of structure.

Mahmood et al. (2016) used empirical relations to calculate "V_s" form standard penetration test (SPT) values. The values of subgrade modulus can be estimated by the following laboratory and field tests:

i. Plate load test (ASTM D1194)

ii. Triaxial Test (D2850)

Table 2.2: Required soil properties for SSI in indirect method, Mahmood et al. (2016).

Depth (m)	**Soil Type**	**Average Thickness (m)**	**USCS**	**Allowable Bearing Capacity, q_a (KPa)**	**Poisson's Ratio**	**Shear Wave Velocity V_s (m/s)**	**Shear Modulus $G_s 10^{-3}$ (KPa)**	V_{savg} **(m/s)**
0 to 2.1	Sc	2.1	CL-ML	-	0.4	373	2504.3	354.1
2.1 to 5.2	Sc	3.1	CL-ML	143.5	0.4	386	2681.9	
5.2 to 8.3	Sc	3.1	CL	-	0.45	364	2384.9	
8.3 to 10	SD	1.7	CL-ML	-	0.4	314	1774.8	
10 to 19.8	SD	4.9	CL	-	0.45	342	1920.3	Sc

2.4.1 Soil Modelling

The modeling soil medium below the structure is standout amongst the most essential parameter in the soil structure interaction (SSI) analysis. Different approaches have been available to model the SSI on shallow and embedded foundations which are as follows:

i. Winkler's model (spring model)

ii. Lumped parameter on elastic half space

iii. Numerical methods

2.4.1.1 Winkler's Model

Winkler's method defines the soil medium utilizing horizontal and vertical closely spaced, linear elastic springs which are identical and mutually independent. As per Winkler's theory foundation deformation happens only at loaded areas. In Wrinkle's approach, linear springs have utilized to model soil stratum, Fig. 2.8.

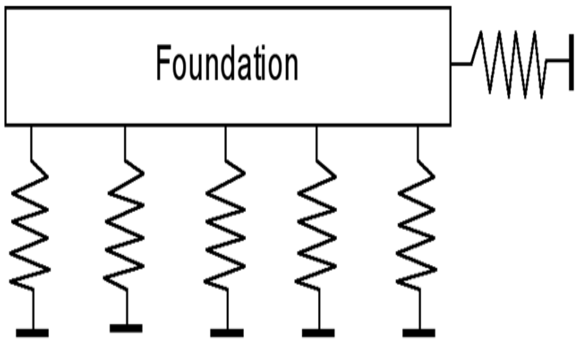

Figure 2.8: Winkler Foundation.

The pressure-deflection relation at any point is given by:

$$F = k\Delta$$

Where, F = pressure from superstructure, k = modulus of subgrade reaction and Δ = deformation. "k" is the ratio of pressure, "F" to de formation "Δ" at any given point of the contact surface, i.e. $k = F/\Delta$, Dutta., (2002); Baker., (1957); Vesic., (1961); Kramrisch et al. (1961); Bowles (1996); and Brown (1977) directed their research following Winkler methodology owing to its simplicity. The value of "k" relies on the accompanying parameters, i.e. type of the soil, depth from existing surface level and dimensions of the foundation area. In the Winkler's theory stiffness of the related elastic springs is the main parameter to design the physical behaviour of the soil medium. Consequently, the numerical estimation of soil springs must be resolved with care in order to implement in a real problems. Dutta et al. (2002) suggested the Winkler approach inspite its confinements produce reasonable performance and very easy to model. Therefore, this idealization is preferred for practical purposes because of its simplicity.

2.4.1.2 Lumped Parameter on Elastic Half Space

Bowles, (1996) explained that in the lumped parameter strategy, the impact of frequency dependent soil-flexibility on the behaviour of complete structural system is higher than the springs values acquired from frequency independent behaviour determined by Winkler model.

2.4.1.3 Numerical Methods

Numerical approaches are classified into two major techniques i.e. substructure method and direct approach. In numerical methods, the impact of soil is considered by modeling them in two or three dimension using FEM. The upside of numerical methods is the inelastic behaviour of soil which can be considered by numerical incorporation utilizing equations of motion in time domain.

Prior to the SSI analysis, this procedure demands the independent ground motion record at structure base, Clough., (2003). The 3-D SSI system is shown in Fig. 2.9.

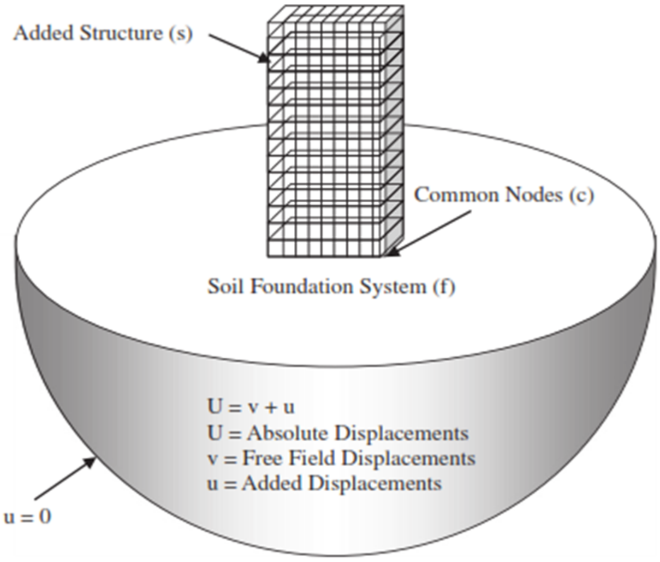

FIGURE 2.9: 3D SSI model, Tabatabaiefar et al. (2013).

Two further approaches of numerical methods are i.e. indirect method and direct approach.

2.4.1.3.1 Indirect Method for SSI In indirect approach, SSI system is isolated into three steps, which are then joined to analyse the real SSI system. Kramer, (1996) described that the superposition for this technique assumes linear soil and structure behaviour. Varun. (2010) reported the three stages for the analysis of SSI utilizing indirect approach.

i. Estimation of foundation Input Motion (FIM) by assuming the massless condition for structure as well as substructure.

ii. Calculation of impedance function, which was stiffness and damping characteristics of SSI system.

iii. Dynamic analysis of the structure by incorporating SSI.

2.4.1.3.2 Direct Method for SSI It is the direct method of soil-structure system, in which analysis is being performed in a single step. Sketch of a direct approach of SSI system is shown in Figure 2-4. In these methods, typically, the soil is modelled as solid finite elements and the superstructure as finite beam elements. Desai et al. (1982); Mirhashemian et al. (2009); Tabatabaiefar et al. (2010); Gouasmia et al., (2010) have studied dynamic response of soil-structure systems adopting direct method for modelling soil-structure interaction to achieve accurate and realistic analysis outcomes. Carr, (2008) believes that the advantage of this method in fact is its versatility to deal with complex geometries and material properties. However, data preparation and complexity of the modeling makes it difficult to implement it in every-day engineering practice. In addition, advanced computer programs are used for analysis. In this method, an exact nonlinear analysis is possible, Borja et al. (1992).

2.5 Simplified SSI Techniques

Lagoras et al. (2011) evaluated static pushover analysis in view of optimum building design. The capacity spectrum method was outclassed as it overestimated the demand. The dissimilarity of result between the N2 method with coefficient displacement method was somewhat little for low and medium level earthquakes. Mekki et al., (2016) adopted N2 method due to its ability, simplicity and applicability to furnish structure displacement with reasonable accuracy manageable computational efforts.

2.5.1 N2-SSI Method

The decision for this method has been made due to its simplicity and capability to give structure displacement with less calculation efforts. A streamlined model that takes SSI effects is a SDOF replacement oscillator (Fig. 2.9) has been utilized in this method. Demand spectra and capacity spectra are two essential components to be considered in this method for evaluation of flexible base structures.

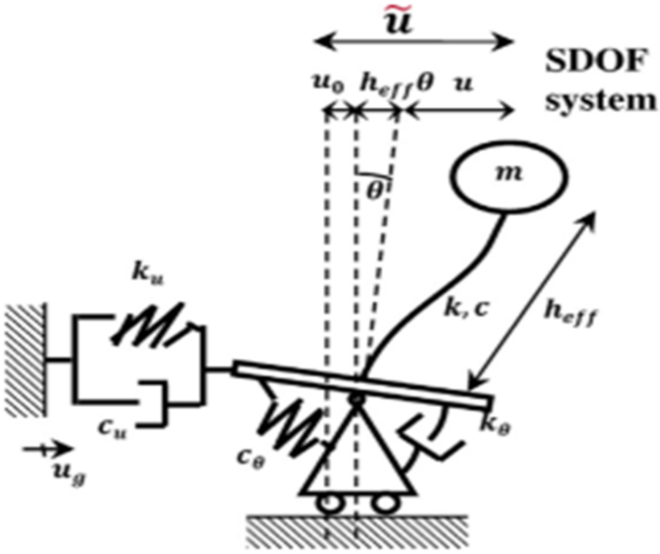

FIGURE 2.10: N2-SSI: Soil-SDOF oscillator model, Mekki et al. (2016).

Equations for time period lengthening and damping ratio are as follows:

$$\tilde{T} = T\sqrt{1 + k\left[\frac{1}{k_u} + \frac{h_{eff}^2}{k_\theta}\right]}$$

$$\tilde{\xi} = \frac{T^2}{\tilde{T}^2}\xi + \left[1 - \frac{T^2}{\tilde{T}^2}\right]\xi_g + \left[\frac{T_u^2}{\tilde{T}^2}\xi_u + \frac{T_\theta^2}{\tilde{T}^2}\xi_\theta\right]$$

Where, $T = 2\pi\sqrt{m/k}$ is the period of structure for rigid/fixed base condition, $T_u = 2\pi\sqrt{m/k_u}$ & $T_\theta = 2\pi\sqrt{m/k_\theta}$ are the natural periods in translation and rocking motion of the structure for rigid conditions. "k_u" is translational stiffness and "k_θ" are the rocking stiffness in their respective modes and "h" is effective height of the structure.

$\xi = \pi c/kT$ is the damping ratio for rigid/fixed base conditions, $\xi_u = \pi c_u/k_u\tilde{T}$ and $\xi_\theta = \pi c_\theta/k_\theta\tilde{T}$ are the soil damping ratios for horizontal and rocking mode of the foundation. "ξ_g" is the soil damping.

Typical practice does not incorporate the "k" value for flexible foundations. Instead, foundation springs are distributed across the extent of the foundation. Distributed springs method allows the foundation to deform in a natural manner at the given load imposed by the superstructure and the spring reactions. That is why, N2-SSI method typically neglects the "k" value of raft to introduce flexible foundation effects.

Mekki et al. (2106) evaluated the seismic behaviour of RC structures by including SSI effects. Development of fragility curves at desired performance points had been made by using N2-SSI method. It was found that N2-SSI was capable of producing fragility curves. These curves were used to represent the likelihood of structural damages under desired level of seismic excitations.

2.6 Summary

The building structure should be designed with a realistic and reliable comprehension of risk and economic optimization. SSI has risen as intense and effective method of analysis and design to achieve aforementioned objectives for building structures. SSI impact on seismic behaviour of structures has been described with the help of past literature. SSI lengthens the time period and intensifies the structural response. Direct analysis of SSI gives more practical approach yet the direct solution of SSI is troublesome and rarely used in practice. The indirect analysis approach analyzes inertial response and kinematic response into separate parts, which are then combined to formulate the complete solution.

Different approaches to incorporate SSI system have been discussed in accordance with literature review. Wrinkler's is most widely used due to its simplicity, whereas Lumbed parameter space is the modification of Winkler's model on elastic half. Numerical methods are the advance form of SSI modeling utilizing the FEM. The significance of this method is due to its ability of considering soil nonlinearity.

Chapter 3

Discussion

3.1 Background

The present attempt endeavor to explore SSI techniques in structure design with respect to soil medium. The choice of procedure relies on the true behavior of the SSI system. This behavior can be assessed, if an appropriate design methodology has been opted to model the soil medium. The main parameter of foundation design is the distribution of contact pressure at the foundation and soil interface. The distribution of pressure may differs depending upon the foundation behavior (i.e., rigid or flexible) and rigidity of supporting soil (clay or sand etc.). In order to incorporate SSI in analysis and design of structures, N2-SSI model is used. Seismic response of RC structures has been studied through literature research with respect to linear and non-linear pushover analysis. There is a need to develop guidelines to incorporate SSI in conventional practice of building structure analysis and design. On the basis of this need, simplified criterion has been established and solution to SSI problems has been given in an efficient way to make SSI practice easy to adopt by practicing designers.

3.2 Identification of an Efficient Method for SSI

Building code of Pakistan permits force-based approach and NLRHA approach which is adopted mainly from the following engineering standards and guidelines:

- UBC (1997), Uniform Building Code, International Conference of Building Officials, Whittier, California, USA.
- IBC (2006), International Building Code 2006.

But these standards partially address the flexible foundation effects. In these standards, the phenomenon of kinematic interaction is not sufficiently described. The decrease of seismic demands of structures due to ground motion is partially adopted, Stewart et al. (2004).

3.2.1 Limitations of Structural Analysis and Design

There is no single reference document available to recommend analysis and design parameters by accounting soil-structure interaction effects for following reasons:

- Prevailing code of practice in Pakistan is Building Code of Pakistan (BCP)-2007 which referrers mainly to UBC-1997 and ACI-318-05.
- Equivalent static procedure is outlined in ACI 371R-08 and ASCE 7-05 but these codes suggest site specific acceleration amplification which makes it difficult to use ACI 371R-08 strictly for regions outside United States. Therefore, the concept of equivalent static procedure is taken from ACI 371R-98 and the stepwise procedure to be adopted for Pakistan region is taken from UBC-1997 (ASCE-7-95)/BCP-2007.

3.3 Adopted Procedure by Practicing Designers

The procedure given in following sections is based on the traditional practice adopted by practicing engineers.

3.3.1 Final Geotechnical Recommendations

According to geotechnical studies, following considerations are required from geotechnical engineer(s).

- Depth of footing
- Ultimate bearing capacity
- Effective bearing capacity
- Seismic zone
- Soil profile type

Example of detail soil parameters were presented in Table 2.2.

3.3.2 Architectural Design

The process of structure design has been done subsequent to getting an architecture plan. It includes the induction of columns. Location of beams and slabs has been assured. Stairs and selection of foundation type are accomplished.

3.3.3 3D Models and Materials

Finite element model (FEM) of structures has been prepared in computer structure programs, i.e. SAP2000, Etab, FLAC 2D, etc. for fixed/rigid base conditions. Materials details and loads patterns, cases and combinations have been assigned to structural and non-structural elements at this stage.

3.3.4 Design of Foundation

Finite element model (FEM) of foundation has been prepared in computer structure programs, i.e. SAFE.

3.3.5 Engineering Drawings

The ultimate step of the design process is to create and generate plan of foundation and structural components of the building, calculation and design checking.

3.4 Stepwise Procedure to Incorporate SSI

3.4.1 Soil-structure Ratio

Utilizing the Eq. (2.1) (NIST GCR 12-917-21) the structure-to-soil ratio (h/V_sT) can be computed to evaluate the degree of SSI impacts on the structural responses. According to NIST GCR 12-917-21 when, $h/V_sT > 0.1$, SSI influences significantly on the structural response while for, $h_s/vT < 0.1$, SSI impact on building response are somehow little. Where "h_s", "V_s" and "T" describes the building height, base shear and time period of the building, respectively, with fixed base condition.

3.4.2 N2-SSI Analysis

N2-SSI technique provides a unique simplified and easy to adopt model to treat a complicated problem such as non-linear SSI. Mekki et al., (2016) adopted N2 method due to required simplicity associated to this method, its applicability and fewer calculations with high accuracy.

3.4.3 Boundary Conditions for SSI Modeling

In N2-SSI method, soil medium has been modeled as replacement oscillator concept shown in Fig. 2.10, Mekki. (2016). The soil springs and dashpots are given in Table 3.1 and Table 3.2, respectively.

TABLE 3.1: Values of soil springs based on N2-SSI.

K_U	Horizontal mode	$\frac{8}{3(1-v)}Gr_\theta^3$
K_θ	Rocking mode	$\frac{8}{2-v}Gr_u$

TABLE 3.2: Values of soil dashpots based on N2-SSI.

C_U	Horizontal mode	$\frac{4.6}{2-v}\rho V_s r_u^2$
C_θ	Rocking mode	$\frac{0.4}{1-v}\rho V_s r_\theta^4$

Where; "G" is shear modulus of soil, "v" is the Poisson's ratio of soil. "r_θ" and "r_u" are the foundation radii computed distinctly for translational and rotational deformation modes to match the area (A_f) and moment of inertia (I_f) of actual foundation.

where

$$r_u = \sqrt{\frac{A_f}{\pi}}$$

and

$$r_\theta = \sqrt{\frac{4I_f}{\pi}}$$

Three DOFs are typically required to define the stiffness (which is a function of displacement) properties of a structure, i.e. lateral displacement and two joint rotations. Whereas, for dynamic analysis of real 3D buildings, only one DOF (i.e., lateral displacement) is required if it is idealized with mass concentration at one location, typically the slab level. That is why, it is called a single degree of freedom system (SDOF). N2-SSI method is based on SDOF oscillator model in which concentrated mass has been introduced on the massless stiffness and dampers as an analogy to real 3D building. In real buildings, the mass has been concentrated at the slab level supported on columns, which can be assumed as massless as compared to slab. The rotational components of seismic motion (rocking) are not measured during earthquakes. These can be estimated from the measured translational components. Since N2-SSI is dominant in SDOF, but real buildings are 3D. The same concept may be extended for 3D buildings by considering each column as SDOF system.

The kinematic interaction problem is complicated by the influence of piles. With the availability of vertical springs along the length and at the bottom of the piles, N2-SSI method may solve the conditions for simple pile foundation.

3.5 Summary

Present practicing techniques did not well incorporate the flexible foundation conditions. The decrease in seismic demand of structures with respect to ground motion is not sufficiently described in these procedures. Conventional design procedure was discussed and step-wise guidelines have been developed to incorporate SSI in adopted procedure. The N2-SSI method was opted to introduce flexible soil behaviour. The selected method is non-linear static SSI technique and has a capacity to apply for any structure type and geotechnical environment.

Chapter 4

Conclusion and Recommendations

4.1 Conclusion

A simplified approach to incorporate SSI in analysis and design of structures has been identified through literature research of preferably last 5 years. This effort has been made to convince practicing designers to opt the SSI practice in their analysis and design. Empirical method(s) and lab procedures were gathered to obtain required soil data to incorporate SSI approach in performance base seismic design procedures. This study concludes;

- Modeling of building with SSI required additional efforts, yet it gives more realistic solution with elastic foundation.
- N2-SSI method has found to be an efficient and easy to adopt approach to incorporate SSI in analysis and design of structures.
- The identified method utilises equivalent SDOF replacement oscillator approach in which the soil effect is introduced on the non-linear response of the structure.

- This method proved its efficiency due to required simplicity associated to this method, its applicability and fewer calculations.

4.2 Recommendations

Following are the recommendations;

- Validation of this identified efficient method and studies on example application to demonstrate the benefits associated with this approaches are required to be done.
- For real scale design, acquisition of ground motion data for particular site is typically the part geotechnical consultant(s) to cooperate the structure engineer(s) in specialized methodologies on projects involving SSI.

Bibliography

Demirol, E. and Ayoub, A. S. (2017). Inelastic displacement ratios of SSI systems, *Soil Dynamics and Earthquake Engineering*, Elsevier, 96, pp. 104-114.

Dutta, S. C. et al. (2016). Gorkha (Nepal) earthquake of April 25, 2015: Actual damage, retrofitting measures and prediction by RVS for a few typical structures, *Soil Dynamics and Earthquake Engineering*, Elsevier, 89, pp. 171-184.

Fatahi, B., Tabatabaiefar, H. R. and Samali, B. (2011). Performance Based Assessment of Dynamic Soil-Structure Interaction Effects on Seismic Response of Building Frames, *Geo-Risk 2011 (ASCE)*, pp. 344-351.

FEMA 440, (2005). Improvement of Nonlinear Static Seismic Analysis Procedures, *Federal Emergency Management Agency*, Washington, D.C., (June).

Joy, P. V., Kuriakose, B. and Mathew, M. (2016). Pushover Analysis of Buildings Considering Soil-Structure Interaction, *Applied Mechanics and Materials*, 857, pp. 189-194.

Karapetrou, S. T., Fotopoulou, S. D. and Pitilakis, K. D. (2015). Seismic vulnerability assessment of high-rise non-ductile RC buildings considering soil-structure interaction effects, *Soil Dynamics and Earthquake Engineering*, 73, pp. 42-57.

Kramer, steven L. (1996). Geotechnical Earthquake Engineering, *Kramer*, 1996, pp. 376.

Lagaros, N. D. and Fragiadakis, M. (2011). Evaluation of ASCE-41, ATC-40 and N2 static pushover methods based on optimally designed buildings, *Soil Dynamics and Earthquake Engineering*, Elsevier, 31(1), pp. 77-90.

Mahmood, K. et al. (2016). One dimensional equivalent linear ground response analysis-A case study of collapsed Margalla Tower in Islamabad during 2005 Muzaffarabad Earthquake, *Journal of Applied Geophysics*, Elsevier B.V., 130, pp. 110-117.

Mekki, M. et al. (2016). Seismic behavior of R.C. structures including soil-structure interaction and soil variability effects, *Engineering Structures*, 126(7), pp. 15-26.

Mekki, M. et al. (2014). Soil-structure interaction effects on RC structures within a performance-based earthquake engineering framework, *European Journal of Environmental and Civil Engineering*, 18(8), pp. 945-962.

Modirzadeh, M., Tesfamariam, S. and Milani, A. S. (2012). Performance based earthquake evaluation of reinforced concrete buildings using design of experiments, *Expert Systems with Applications*, Elsevier Ltd., 39(3), pp. 2919-2926.

Muljati, I., Asisi, F. and Willyanto, K. (2015). Performance of force based design versus direct displacement based design in predicting seismic demands of regular concrete special moment resisting frames, *Procedia Engineering*, Elsevier B.V., 125, pp. 1050-1056.

NEHRP Consultants Joint Venture (2012). Soil-Structure Interaction for Building Structures, *Nist Gcr*, 12, pp. 917-21.

Rayhani, M. H. and El Naggar, M. H. (2008). Numerical modelling of seismic response of rigid foundation on soft soil, *International Journal of Geomechanics*, 8(6), pp. 336-346.

Sivrikaya, O. and Toğrol, E. (2006). Determination of undrained strength of fine-grained soils by means of SPT and its application in Turkey, *Engineering Geology*, 86(1), pp. 52-69.

Tabatabaiefar, S. H. R., Fatahi, B. and Samali, B. (2013). Seismic Behavior of Building Frames Considering Dynamic Soil-Structure Interaction, *International Journal of Geomechanics*, 13(1), pp. 409-420.

Tabatabaiefar, H. R. and Massumi, A. (2010). A simplified method to determine seismic responses of reinforced concrete moment resisting building frames under influence of soil-structure interaction, *Soil Dynamics and Earthquake Engineering*, 30(11), pp. 1259-1267.

Tabatabaiefar, H. R., & Fatahi, B. (2014). Idealisation of soil-structure system to determine inelastic seismic response of mid-rise building frames. *Soil Dynamics and Earthquake Engineering*, 66(11), pp. 339-351.

Thaker, T. P., Rao, K. S. and Gupta, K. K. (2009). One dimensional ground response analysis of coastal soil near Naliya, Kutch, Gujarat, *Igc*, (December), pp. 531-535.

Veletsos, A. S. and Meek, J. W. (1974). Dynamic behaviour of building?foundation systems, *Earthquake Engineering & Structural Dynamics*, 3(2), pp. 121-138.

Vrettos C. (2014). Soil-structure Interaction, *Encyclopedia of Earthquake Engineering*, 9, pp. 1-16.

Zameeruddin, M. and Sangle, K. K. (2016). Review on Recent developments in the performance-based seismic design of reinforced concrete structures, *Structures*, Elsevier B.V., 6, pp. 119-133.

Annexures

SSI Softwares

Given below the brief introduction of softwares and tools widely used around the globe for SSI modeling in analysis and design of building structures.

A-1: OpenSees

OpenSees (Open System for Earthquake Engineering Simulation) allows users to create finite element applications for simulating the response of structural and geotechnical systems subjected to earthquakes.

A-2: LUSAS

In LUSAS, detailed soil and structure model can be analyzed in single program i.e., springs, 2D and 3D, linear and non-linear etc. It can model dynamic effects in SSI.

A-3: Plaxis

Plaxis can efficiently be applied as a tool in seismic soil-structure interaction. This software is based on the finite element method and intended for 2D and 3D engineering, design and analysis of soil and rock deformation, stability and soil structure interaction.

A-4: ABAQUS

ABAQUS is one of the widely used software for finite element simulation of soil-structure interaction problems.

Flac 2D & 3D

FLAC 2D & 3D is designed to accommodate any kind of geotechnical engineering project where continuum analysis is necessary. This software is widely used in analysis, testing and design of soil-structure interface.