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A critical review on structure-soil-structure interaction

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Abstract

The purpose of this paper is to review computational methods in structure-soil-structure interaction. As a result of globalization, buildings are located close to each other. This issue happens especially in big cities, making the study of structure-soil-structure interaction as an essential part of structural design process. The effect of soil medium, on which the building structure stands, especially on seismic behavior of building is well known. The effects of structures standing in a close distant to each other is the main issue in structure-soil-structure interactions. In this paper, analytical models of soil are reviewed. After a review on different analytical models of soil, the concepts and the computational efforts in the field of interaction between soil and adjacent buildings are discussed in order to provide the reader with the benefits and weaknesses of each concept. Different computer programs which suit structure-soil-structure interaction analysis and their main abilities are briefly reviewed as well.

Keywords: *structure-soil-structure interaction, seismic performance, soft soil*

1. Introduction

Tremendous efforts have been done in the field of interactions within soil and structure. It is anonymously accepted that considering a building structure separated from its surroundings may result in overestimated either underestimated responses. Having this in mind, considering the effect of soil or other structures on the building structure's response is of a vital importance. Different situations in which the structure is built, i.e. building the structure on soft soil or existence of adjacent buildings, which are trembling, make the study of their interactions as a necessary part in the design procedure. There are several parameters on which the structure damage during an earthquake is rely such as: system properties including the shear waves speed of travelling, building dimensions and the structural properties of used components. Other factors are some ratio of building height to foundation dimension, ratio of the main frequency of the structure to the underlying soil and underlying soil to the excitation, and finally relative stiffness of the superstructure to the subsurface. The effect of underlying soil on the structure's behavior or vice versa categorized in two effects: inertial and kinematic effects. Inertial interaction is the effect on which several studies has been conducted and refers to the resulting interaction between the ground time history and superstructure due to the building's movement. On the other hand, kinematic interaction is usually defined as the difference between the ground motion recorded at the foundation level and the response which would have been expected in the absence of the structure. There are three main reasons which make the study of soil structure interaction necessary.

First, the structure's period, compared to its fixed-base model, is generally lengthened, when the SSI is taken into account. This would lead the fundamental period of the structure to the longer period region of design spectrum which usually contains lower pseudo acceleration response values. But in some cases, such as a stiff building, it may be pushed to the higher pseudo acceleration region [1]. Second, the underlying soil itself will act as a damping mechanism as it shows nonlinear response with relatively soft material properties [3, 4]. Third, the response modification coefficient

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which is used to decrease seismic input loading on a structure which is assumed to behave in the elastic region under a given excitation [2]. This paper aimed to review the analytical and computational efforts in the field of soil-structure and structure-soil-structure interactions and provide the reader an overview of these efforts.

2. Analytical models of soil in literature

The concept of soil-structure interaction (SSI) has received a great attention amongst the researchers as it relates soil and building structural mechanics, in line with structural dynamics and earthquake engineering. First researches on SSI have been done in late 20th century due to the emergence of nuclear power planets. In recent decades great effort is dedicated to dynamic SSI for building structures lying on soft soil [5, 6].

Generally speaking, soil types in which the shear wave velocity is less than 600 m/s, impose a great modification on the buildings seismic responses due to the strong interaction between soil and structure. This especially happens for moment resisting structures. These modifications are summarized as follows:

A. increasing the natural period of the structure as well as its damping

B. increasing the lateral displacements

C. Changing the base shear (this depends on the frequency content of input disturbance and dynamic characteristics of the structure as well as the underlying soil.

Analyses of SSI effects during an earthquake is usually done by one of the two proceeding methods [7]:

A. A complete interaction analysis which concerns complete the variation of structure and underlying soil.

B. An internal analysis which assumes that motions in the underlying soil are the same at all points above foundation depth.

2.1. Structure-soil-structure interaction under static and dynamic loading conditions

Numerous researches concerned with the effect of SSI under static loading. These studies [8, 9] demonstrated that force quantities are modified due to the static loading. Some studies investigated SSI in three dimensional space. It is realized that a two dimensional study of soil structure interaction would overestimate or underestimate the responses. (Martel RR, Tanabashi R, Ishizaki H)

Studies in the field of dynamic loading proved that due to the support flexibility of real building structures [9,10], overall stiffness of the structure may face a serious reduction and as a result, the period of structure will increase, and this will definitely modify seismic response of the structures [11].

Attempts for developing a simple model which best accounts for soil media characteristics in SSI indicates two basic approaches namely Winkler model and elastic continuum model. However due to the drawbacks involved in each model, several improvements have been done on these theories, some of which are summarized below.

2.1.1. Winkler Model

In this idealization a system of springs account for the soil behavior. These springs are identical but mutual independent, closely located to each other and behave linearly elastic. It is assumed that deformation of foundation is due to any arbitrary loading is limited only to the loaded area. A schematic of this idealization is shown in figure 1.

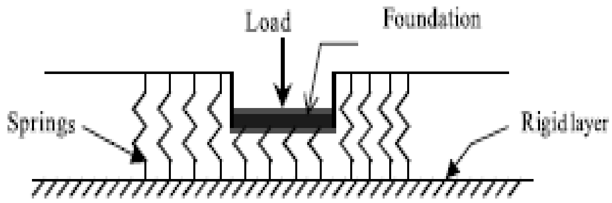

Figure 1. Winkler idealization of soil media [11]

The improved versions of Winkler model are [11]:

A. Filonenko-borodich foundation: The connectivity of the individual springs in the Winkler model is modified in this approach and their connectivity is achieved through a thin elastic membrane which is subjected to a constant tension T. This membrane which connects the springs is attached at the top ends of the springs and the interaction of the springs is achieved by means of the tension force in the membrane.

B. Hetenyi's foundation: This model can be regarded as an idea connecting two Winkler foundation and isotropic continuum approaches. By means of an elastic beam either an elastic plate, the connection of individual springs is achieved. Flexural deformations are only assumed for this beam (or plate). Further examples are given in [18, 19].

C. Pasternak foundation: In this approach, by connecting the ends of the springs to a beam or plate which only undergoes shear deformations. Detailed information and analytical solutions for this approch are available on [20-22].

D. Generalized foundation: The basic idea of this approach is that the moment at each point of contact is proportional to the angle of rotation and Winkler's hypothesis as well. The reade is reffered to [21] for further information about this approch.

E. Kerr foundation: The modification which this approach has made is to assume a shear layer that the constants of the springs in Winkler's model is different in bottom and top of this Layer [23].

F. Beam column analogy model: This approache solves the classical problem of beam on elastic foundation [24] by introducing a new subgrade model.

G. New continuous winkler model: This method the interconnection is achieved by intermeshing the the springs (instead of the individual springs in the Winkler model) [25, 26].

A schematic of the first 4 approaches is shown in figure 2.

2.1.2. Elastic Continuum Model

The origin of this idea is probably from the work of Boussinesque. Soil is a composition of discrete particles which are compacted by inter granular forces. This approach uses the theory of continuum mechanics to represent the soil behavior. In this idealization soil is considered as an isotropic material. In this approach the simplicity of the input parameters along with the beneficial information it brings about the stresses and deformations, made it a preferred method over the Winkler idealization. However, one may have consider the inaccuracy of this method in calculated reactions at the boundaries of the foundation.

Improved versions of continuum model are:

A. Vlasov foundation:
B. Reissner foundation

In the first approach, variational principle is implemented to develop the continuum model [27, 28]. Certain limits are imposed to the possible deformations of an elastic layer through this approach. In the second approach, based on the following assumptions a relationship for pressure deflection at the interface slab and subgrade is considered: the first assumption is that in plane stresses throughout the foundation is small and can be neglected and the second assumption is that the horizontal displacements at the upper and lower surfaces of the foundation layer is zero.

Further information about the improved versions of both Winkler and continuum model can be found in reference [11].

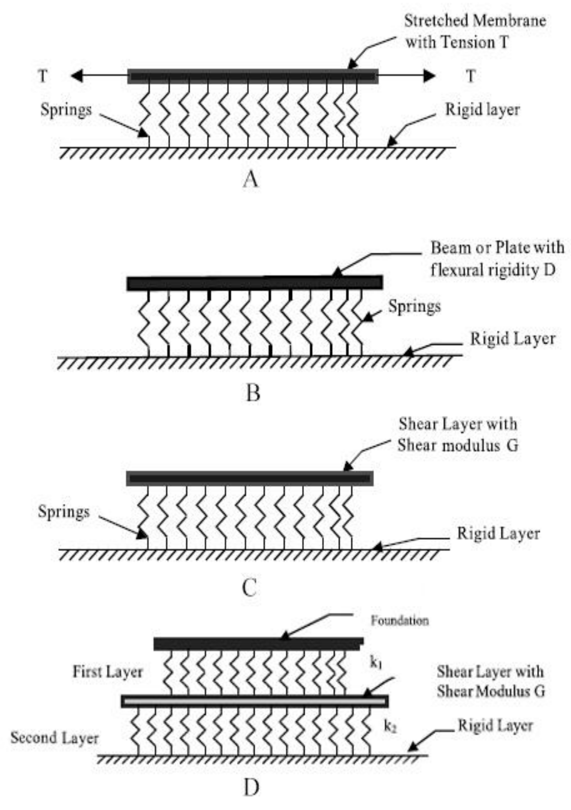

Figure 2. Improvements of Winkler model A. Filonenko-borodich foundation B. Hetenyi's foundation C. Pasternak foundation D. Kerr foundation [11]

2.2. Dynamic soil-structure interaction

In 2000, a study has been conducted by C. B. Crouse in which the energy dissipation in SSI has been surveyed. The importance of this study was upon implementing dampers and isolators such as friction dampers, fluid dampers and isolators. As noted in [14], the SSI could significantly be beneficial as it cause a vast amount of reduction in buildings' seismic response. Experiments done in the field of SSI in line with theoretical calculations have also shown the large amount of modal damping ratios for some type of structures such as mid-rise buildings and nuclear power plants.

The procedure used for modeling energy dissipation in SSI analysis for structures other than nuclear power plants is to model the structure in a commercial software suitable for dynamic analysis. a schematic view of soil structure interaction is shown in figure 3.

These programs use several translational and rotational springs attached to the base of the structure, so that they are able to model foundation-soil interaction. In this phase, foundation stiffness is estimated but no estimation is considered for foundation damping. However, the composite modal damping ratio for modes of soil vibration in soil-structure system depends on the foundation and structural damping as well as the interaction degree between foundation and underlying soil. Considering vertical and horizontal vibration, foundation damping is highest for these situation and lowest for rocking motion. In this case again, foundations damping ratio is significantly greater than 5% damping ratio which is usually considered for typical buildings. Studies in [15] have represented a simple procedure for deriving estimation of modal damping ratios in SSI systems. The reader is referred to [15] for detailed examples on seismic design of a tank, considering SSI energy dissipation.

Dynamic SSI effects especially lower Eigen frequencies. Therefore, it causes an increase in modal damping ratios of the system and the probability of occurring complex valued frequencies increases. The fundamental frequencies and modal damping ratio of the coupled system are highly sensitive to the stiffness of the soil. It is interesting that the associated mode shapes are not dependent to the soil stiffness [16].

Givens and Stewart stated that input excitations which are used in a soil-foundation-structure system which in time history analysis may be modified relative to those of free field excitations in order to be able to account for kinematic interaction effects, foundation springs and dashpots so that they can represent foundation- soil impedance and a structural model [41]. Guidelines for evaluation of kinematic interaction in line with foundation impedance for realistic conditions is outlined in [42].

Garcia studied the influence of soil-structure interaction in the analysis and design of RC frame buildings. Both the influence of soil-structure interaction in dynamic response of the structure and the implications of this interaction in seismic design of buildings are studied in his work [43]. He mentioned in his work that increasing the vibration period and system damping as well as decreasing the horizontal spectral acceleration values is upon considering soil-structure interaction effects in analysis and design of s 6-story RC frame building.

Gerolymos and Gazetas developed a nonlinear Winkler-spring method for response of caisson foundations under the static, cyclic and dynamic loading conditions. By means of a variety of experimental and analytical data, they developed a numerical methodology for calibrating modal parameters [40]. In an earlier study, the dynamic response of an embedded caisson in an elastic half space which is subjected to inertial and kinematic loading. Figure 4 represents the corresponding model. Calibrating the model response predictions and results of 3D wave propagation results, the Winkler spring stiffness and damping parameters were obtained [44]. There are two main procedures which are used in seismic analysis of buildings in line with considering soil structure interaction effects: a. elastic half space theory and b. lumped mass (lumped parameter) [45]. It is widely mentioned in literature that the first approach yields more reliable responses and is more general compared to the other approach. Chen et al. studied the effects of structure soil structure interaction on the seismic response of buildings with inerter system and they found that considering SSI effects, the natural period of a structure controlled by an inerter system is lengthened and its dynamic characteristics are also altered [48]. They also demonstrated that effectiveness of inerter system in energy dissipation may decrease taking into account structure soil structure interaction effects. Figure 5 represents their mechanical model.

Researches on SSI are briefly summarized in table 1.

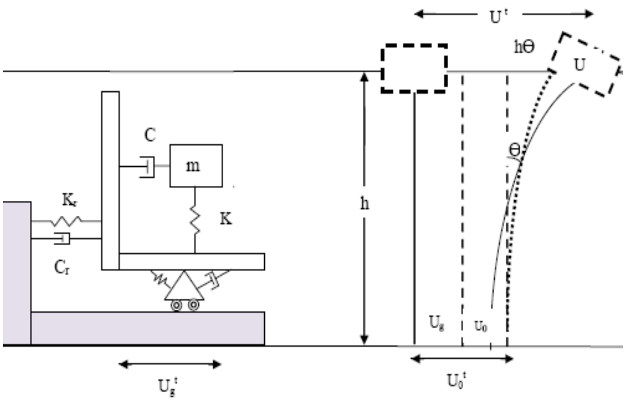

Figure 3. Physical model of soil structure interaction

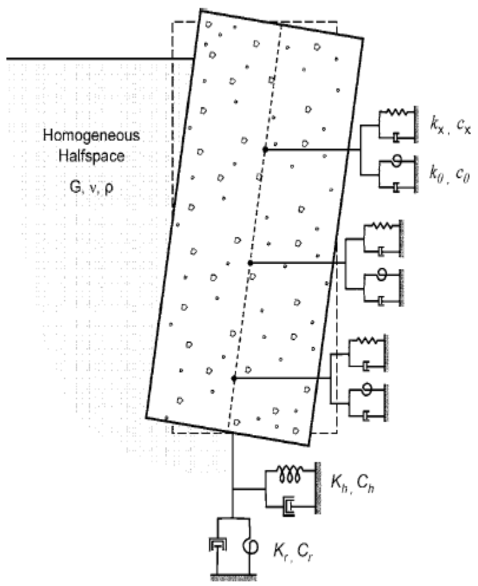

Figure 4. The four types of springs and dashpots for the analysis of inertially and kinematically loaded caissons [40]

3. Structure-soil-structure interactiom

In the previous section soil-structure interaction has been studied and analytical models utilized in soil analysis were briefly reviewed. Another important influence on the structures' behavior is caused by structure-soil-structure interaction (SSSI). The structure-soil-structure interaction is defined as the interaction in the soil between two adjacent buildings [29]. This interaction concerns with the dynamic interaction amongst several buildings located close to each other. This dynamic disturbance may be a seismic wave or an imposed external load. For the analysis under seismic wave first the input matrix of motion should be determined. In this case, each foundation which diffracts the incidence wave field is regarded as a secondary disturbance producer which affects adjacent buildings. Vicencio and Alexander evaluated the effect of soil-structure-soil interaction between two buildings. In this study, different parameters of the buildings, inter-building spacing and soil type were studied under seismic ground motion input. They introduced an extended method which enables higher modes interaction between buildings with considerable difference in height. They suggested that for displacement responses, their extended model is able to capture significant interactions for the cases of a small building which is closely flanked by a taller building [48]. Their study showed that apart from type of the input ground motion, there exist beneficial and detrimental configurations for dynamic characteristics of buildings through study of structure-soil-structure interaction. (Lee IK, Brown PT, 1972)

Several efforts have been done in order to provide a better understanding of SSSI effects. Several analytical, analytical- numerical, numerical methods, experiments and prototype observations have been done which are summarized herein

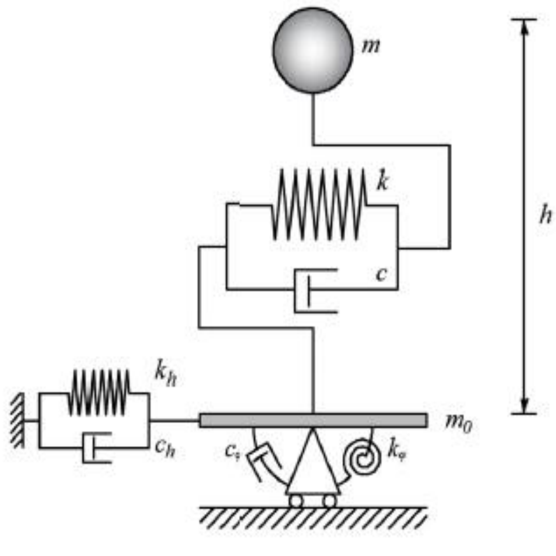

Figure 5. Mechanical model of the SDOF structure on soft soil [43]

3.1. Application of numerical and infield methods in the study of SSSI

Due to the versatility of the numerical methods in capturing all the possible characteristics in modeling many conditions, these methods have been given more attention than analytical methods in studying structure-soil-structure interaction. The advantages of this class of methods are that they are able to model the problem with high precision, and also material behavior such as nonlinear stress- strain behavior, non-homogeneous material conditions, and changing in geometry. Finite element method, boundary element method, hybrid method and general finite element software are the several available methods in numerical modeling of the SSSI problems [36].

The analytical and numerical schemes mostly used in SSSI studies are briefly reviewed in this section:

3.1.1. Finite element, Boundary element and finite difference

For these procedures (FEM, BEM, and FDM) the soil is considered as a material which is represented by its physical parameters like moduli, stiffness, damping ratios. Several numerical methods have been developed in the field soil and the dynamic interaction of soil and structures such as: the finite element method, the boundary element method and the coupling of these two methods [39]. All these methods are concerning with the system's governing differential equations. The way in which the differential equations are approximated cause the differences of each method.

3.1.2. Eulerian and Lagrangian grid points

Two common procedure for definition of grid points of deformation are Eulerian and Lagrangian grid points. In the first approach a grid is defined and no deformation is allowed to occur. If the subjected material deforms, it is allowed to flow over the grid points but the geometry of the overall mesh does not change. In a Lagrangian approach, conversely, the grid is allowed to deform in accordance to the behavior of the material associated with the specified grid point. So, by flowing the material the grid will flow as well.

3.1.3. Explicit and Implicit solution schemes

There are two approaches available in a numerical procedure accomplished by a computer program explicit and implicit schemes. Explicit methods solve the governing equations of motion for a specified point in the future time based on the current state of the system. Whereas, implicit methods solve the equations of motion for both the current and future states of the system simultaneously. Each of these mentioned methods have their own advantages. The simplicity and the free choice of time step are the benefits of explicit and implicit methods, respectively. However, the choice of time step is of a substantial importance in explicit methods and the computational effort of the implicit procedures impose some limits in implementing each of these methods in a given problem.

The idea of coupling foundations was first introduced by Whitman [6]. This started the initial studies in the field of SSSI. However, an increasing tendency towards the SSSI effects occurred due to the growing need of nuclear power plants, as this system consists of a reactor building close to a turbine and control buildings.

Liang have done a series of parametric studies in 1974 [37] and investigated the effects of interaction amongst two rigid mass located on the surface of the soil. Liang studied a 2-D problem and implemented a finite element type formulation in line with a consistent boundary. Lysmer et al. have done a 2-D analysis [38] and also used a 2-D finite element analysis to study the response of a nuclear plant to ground motion in the case of the presence of two adjacent buildings. All the three buildings were embedded in the soil.

Wang investigated the three dimensional dynamic SSSI by the coupling procedure of finite and boundary elements. By implementing the methods mainly based on the FEM one may only be able to deal with soil layers. By the following assumptions Wang developed a coupled FEM-BEM method: a. the displacements are small b. the material is assumed to be linearly elastic and having material damping c. The soil as assumed as a half space or made of layers which are homogeneous, isotropic and elastic with a hysteretic material damping properties. Following results have been achieved through their studies.

1. The distance impose a great deal of effects on the SSSI effects. By increasing the distance, the interaction decreases more noticeably.
2. The interaction cause the coupling among horizontal and vertical displacements to

increase significantly. The direction in which the foundations are aligned have a considerable effect on the coupling.

3. The SSSI effects may have been amplified at the frequencies in the vicinity of the soil layer resonant frequencies. However the natural frequencies of the excited structure can have a greater effect on the amplification of the interaction at the frequencies near to their values.
4. The location of loading have also a great impact on both the excited and the passive structure. Loadings at the locations near to the foundations have the most influence in the structures' responses.

Some experimental and numerical studies have also done in order to investigate the effect of large groups of buildings on the seismic response of a whole system [30, 31]. A 3D boundary element-finite element method is proposed by Padron et al. [32], in which the dynamic through-the-soil interaction analyze between the nearby structures supported by piles is obtained.

The SSSI effects for a one-story shear buildings concerning the effects of SSSI on lateral spectral deformation in line with the vertical and rotational responses is investigated. It is shown that the effects of SSSI on the groups of structures which have similar dynamic characteristics cannot be neglected. Mock-up structures standing on an unmade ground were the subject of a study carried out by Clouteau et al in 2012 [43]. This experimental study have shown that in the case of surface foundation one can neglect the SSSI effects but for embedded foundations the SSSI effects are so important that should not be neglected.

In the field of dynamic analysis some studies have been done that compare the accuracy of different methods. For instance, the accuracy of the two methods of fully nonlinear and equivalent linear have been compared in 2014 by Fatahi and Tabatabaiefar [34]. This study have shown that the responses obtained by the use of equivalent linear method in SSI effects, (mid-rise rise building with moment frame standing on soft soil in this case) are underestimated in comparison to those of obtained by the nonlinear dynamic analysis. So for the mid-rise buildings which are located on soft soils the equivalent linear method cannot be regarded as a suitable procedure [33].

The effects of the type of foundation on seismic performance of buildings' structures have been investigated in 2015 by Hokmabadi and Fatahai [35], the study in which the SSI effects are included. This study have indicated that the type of foundation impose a great deal of effect on seismic performance of buildings considering SSI effects and have to be given attention in the design procedure so as to reach a safe design that is cost-effective as well.

All the aforementioned studies have been concerned with the effects of adjacent structures on the response parameters of the structures through SSSI effects. Some studies are concerned with the effects of adjacent buildings on input excitation, as the essential parameter in SSI studies. Wen et al. conducted a parametric study on the influence of adjacent buildings on the horizontal and torsional input motion for an embedded foundation. The parameters investigated in this study were a. the distance between the embedded foundation and the adjacent structure, b. the natural frequency of the adjacent structure, c. the shape of the adjacent structure and d. the arrangement angle of the adjacent structure have received attention in this study. It has been shown that the presence of the adjacent structure may cause significant variability to the horizontal input motion of the embedded foundation. Moreover, the fluctuation area of the horizontal input motion is in the vicinity of natural frequency of the adjacent structure. In the case of the torsional input motion for an embedded foundation, the presence of an adjacent structure can induce this excitation.

In accordance with previous research works, this study has also shown that the dynamic response of an existing structure may be influenced by the adjacent structures. This is the case especially when the horizontal natural frequency of the adjacent structure and torsional natural frequency of the existing structure are coincident. This would lead to a great deal of modification of the torsional response of the existing structure

In most wrecking earthquakes, soil and structure undergo large deformations and get into nonlinear phase. As literature shows [13], considering the nonlinear properties of soil has a significant effect in the response of a structure. A sensitivity study in 1982 has been done by Matthees and Magiera on the interaction effects of adjacent structures and nuclear power plant under horizontal seismic excitation. In this study, the nonlinear behavior of soil and structure was considered.

A study has been done by S. Naserkhani and H. Pourmohammad [17] in which a numerical analysis of SSI and SSSI effects on seismic response of twin buildings has been conducted. In this study, buildings were modeled as shear buildings and a discrete model representing a visco- elastic half space was implemented as a representation of soil media. Various soil types were considered under ground motion records and the results were compared to each other. It was noted that considering SSSI effects mitigates sol unfavorable effects on buildings' responses compared to the condition in which SSI effects were only considered. It is also mentioned that the type of soil, plays a dominant role in buildings' responses especially in soft to stiff soils. However, hard soils have shown negligible effects on buildings'' seismic responses [11].

Rezaie and Mortezaei studied performance- based plastic design (PBPD) methods according to soil-structure interaction effects. It is mentioned in their work that there are two main parameters in the implementation of the PBPD design method, first the relative target displacement and second, the selected yielding mechanism. As soil effects can modify both of these factors, it is necessary to consider SSI in PBPD design method. PBPD design method is modified in their study to take into account SSI effects. By taking into account the SSI effects, distribution of rebar in beam and columns of a reinforced concrete moment resisting frame has changed. They have noted that decreasing the height of the structure, would result in intensified changes of rebar location [39].

3.2. Computer programs for SSSI studies

Thanks to the rapid grow of computers, several numerical methods were obtained and developed for analysis of SSSI. Finite element method (FEM) is one of these well-known methods. This solution discretize a continuum to several elements of a finite size. FEM is best able to simulate the mechanics of soil and structures and overcome with the complicated geometry and applied loads [12]. However it requires a great number of elements which eventually may lead to inaccuracy. Several computer programs have been developed that made the application of FEM restricted in the field of SSSI studies. These programs are namely: SASSI, CLASSY, FLUSH (fast LUSH), ALUSH (Axisymmetric LUSH), and SASSI. General finite elements programs (e.g. ANSYS) are also available as powerful nonlinear solvers.

Some researches in the field of SSSI are done by study of recorded responses of instrumented structures known as prototype observation. These studies make the prediction of structures' performance better known for the future earthquakes.

CLASSY, FLUSH and ALUSH, perform analyses based on Fast Fourier Transform (FFT). ALUSH and FLUSH are not able to impose dynamic loading and for these two programs it is necessary to consider the accuracy of 3-D analyses.

It is worth pointing out here, that the most reliable program for SSSI studies is perhaps SASSI which benefits from 3-D sub structuring for a discrete half-space adaptation [12]. But one should consider the program verification before any analyses in SASSI, even simple verifications may not be sufficient when complex modeling is intended. Therefore, it is strongly recommended for the designers to gain a comprehensive knowledge in SASSI program before conducting any SSI or SSSI analysis.

Results from analyzing SSSI effects in nuclear industry was compared in SASSI [46] program with those obtained from FEM-BEM method [47, 48].

Table 1. A summary of SSI researches through analytical, experimental and numerical studies

Researcher	Year	Contribution	Foundation	Analysis
Analytical Studies				
Lin and Miranda	2009	4-story asymmetrical building	Springs and dashpot	Arithmetic sum method
Olariu and Movila	2014	2-story asymmetrical building	Springs and dashpot	Spectral acceleration method
Experimental studies				
Todorvska	2002	45m Hollywood storage building	Pile	Ambient vibration test
Mason, Trombetta, Chen, Bray, Hutchinson and Kuttar	2013	Asymmetrical group of symmetrical building	Isolated	Scale down model, Centrifuge testing
Numerical studies				
Venkatesh, Gupta and Pandit	2012	Asymmetrical loading	Raft	3-D nonlinear analysis of soil and 2-D analysis for structure
Tehrani and Khoshnoudian	2014	Planar asymmetry. 5 to 15 story buildings	Shallow	Pushover analysis
Sharma and punit	2014	Different shear wall configuration in tall asymmetrical building	Shallow	3-D nonlinear dynamic analysis
Isbiliroglu and Taborda	2014	Group of asymmetrical small structure	Isolated	3-D nonlinear analysis
Yigti	2013	Asymmetrical cluster of buildings	Shallow	3-D dynamic nonlinear analysis
Irfan, Sunandan Reddy and Mythili	2014	Soft story effect including interaction	Isolated	3-D dynamic nonlinear analysis

4. Conclusion

In this paper SSSI effects which may alter the building structure's response, particularly in dense urban areas, have been reviewed. Basic concepts of soil-structure and structure-soil-structure interactions were discussed and the effective methods for analysis of structure-soil-structure interaction and their advantages were investigated, as well as their drawbacks. Different challenges which designers may be encountered through a comprehensive design of structures were noted. Finally, the computer programs which are available in SSI and SSSI studies were introduced and the basis of each program reviewed.

It is strongly recommended to consider SSSI effects in the design procedure, especially in dense areas or for structures being constructed on soft soil, as neglecting structure-soil-structure interaction may cause either severe damage for structure or economic losses. The brief concluding remarks are as follows:

1. Lumped parameter approach may be helpful for analyzing soil-structure interaction under dynamic loading. However, FE modeling may better account for complex structures.
2. It is acquired to consider soil structure interaction under static and dynamic loading conditions. Therefore, realistic yet simplified models of soil-structure-foundation interaction are necessary.
3. Winkler model is a simple model which yields reasonable responses despite of its limitations. Therefore it is recommended to use this hypothesis in practical problems instead of analyzing fixed-base structure.
4. Discretization the system into a number of elements is a useful method when the effects of material nonlinearity, non-homogeneity and anisotropy are to be considered in a particular case.
5. All modes of the structure are influenced by the dynamic soil-structure interaction effects. Vertical modes are more influenced where soil- structure interaction plays a dominant role, even in a stiff soil condition.
6. Dynamic soil-structure interaction may lead to lower Eigen frequencies for the coupled soil-structure system. It may also increase modal damping ratio and occurrence of complex valued mode shapes.

7. There seems to be a gap in the field of experimental tests in structure-soil-structure interaction. Most of the available literature in the field of SSSI are just theoretical derivations and numerical calculations.
8. Type of the input ground motion can affect linear structure-soil-structure interaction behavior.
9. Displacement responses do not act as the accelerations responses. Therefor when there is huge difference between the heights of the buildings, modal coupling should be considered in analysis procedure.
10. Different configuration of the buildings according to the adjacent buildings configurations, should be considered in order to avoid detrimental structure-soil-structure interaction effects.
11. Considering SSI effects in seismic response of the structures with inerter system, the natural period of a structure controlled by an inerter system is lengthened and its dynamic characteristics are also altered.
12. Taking into account the soil structure interaction effects, for the case of buildings with inerter structural system, the effectiveness of the inerter system in vibration mitigation may be decreased.

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