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Challenges of Soil-Structure Interaction Problems– A Review

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ABSTRACT

This research deals with the review of former research that made to solve the challenges and complexities of both static and dynamic soil structure interaction through discussing advanced computational models and their applications and exploring methods of solving the challenges of soil structure interaction in foundation engineering to provide a guide for the engineering community through the complexes of soil structure interaction. It was found that the numerical analysis for both static and dynamic soil structure interaction using the finite element method with the aid of advanced computional models is ideal for dealing with the non-linearity of soil and structure properties and loading conditions and that the use of interface elements which is essential for idealization of forces between two different mediums and that the interaction effect of adjacent structures cannot be ignored in the seismic design of high raised buildings especially for buildings in the middle and the effect of non-linearity of soil properties can be ignored in seismic design upon increasing in soil stiffness, slenderness ratio of buildings and when the foundation soil was improved. The cost and time of dynamic soil structure analysis can be reduced by using the equivalent pier method, Mohr Columb Model in ABAQUS software, multi step and data-based method and there is a need to add guidelines on the implementation of soil structural interaction in seismic codes in order to include it in the regular design practice of structures. Moreover, it was found that the non-linearity and uncertainty of soil properties greatly affect the safety of structures and it is essential to consider static soil structure interaction analysis to assure safe and economical design of structures.

Keywords: Dynamic soil-structure interaction, Finite element method, Static soil structure interaction.

1. INTRODUCTION

Structures are built on soil, and the foundation transmits static or dynamic loads acting on the structure to the soil. The foundation and superstructure stresses are modified due to the deformation of the soil caused by the static or dynamic loads acting on the structure. The

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change of stresses in foundations due to the interaction between the foundation and soil is defined as soil-structure interaction **(Kunnath, 2020).** The behavior of the interfaces between the foundation and the soil should be included in the models for the analysis and design of structures founded on soil because of the significant effect of relative motions that occur at the interfaces on the overall behavior of the structure–foundation systems. In the Simplified models of computing displacements and stresses in soil, it is assumed that the soil behaves as a linear, elastic and continuous material. But in fact, the soil mostly behaves as a nonlinear, inelastic and discontinuous material **(Desai and Zaman, 2014).** Also, the variety and uncertainty of soil parameters, structure types, and the variety of loading conditions, soil structure interaction modelling is still a challenging topic and these challenges need to be solved in order to provide a better design for structures, especially high and important structures.

This research work presents a review of the previous research work about challenges faced by the researchers in performing both static and dynamic soil-structure interaction analysis such as non-linearity and uncertainty of soil and structure parameters and loading conditions and the methods of the analysis used by the researchers to overcome these problems and that was done by numerical modelling of the structure through the finite element method and the use of advanced computational models to solve the material non-linearity problem and a comparison was made between these methods of analysis also a review of the methods to overcome the high cost of the finite element analysis in seismic design of structures and a comparison was made between them and the lack of standards and guidelines for conducting soil structure interaction in seismic design was discussed. Methods for overcoming the challenges of the soil structure interaction were also mentioned in this research.

2. DYNAMIC SOIL-STRUCTURE INTERACTION

The interaction between soil and foundation caused by dynamic loads or caused by seismic waves acting on the soil is known as the dynamic soil-structure interaction **(Kunnath, 2020)**. Soil-structure interaction has a vital role in seismic design because the energy of an earthquake is transmitted through the ground interacts with structures and influences its response. The accounting of soil structure interaction in seismic design leads to a more realistic estimation of the structure's response, more safety, and a more efficient design that leads to a more realistic seismic design that will prevent the collapse of the structure during earthquakes **(Sitharam et al., 2022)**.

3. CHALLENGES OF ACCOUNTING FOR SOIL STRUCTURE INTERACTION IN SEISMIC DESIGN

The challenges are as follows **(Sitharam et al., 2022)**

3.1 Non-linearity and Variation of Structure and Soil Parameters

The density, damping parameters, and stiffness of the structure, as well as the properties of the ground, such as natural period, frequency, and amplitude of vibration, can be widely varied and will increase the complexity and difficulty in modeling soil structure interaction.

3.2 High Costs

The process of modelling and analysis of structures with variable parameters and soil conditions with complex conditions needs finite element analysis, which requires intensive computation and prolonged time, especially for high and complex structures.

3.3 Availability of Standards and Guidelines

Most standards and guidelines do not present instructions on how to model and analyze, and that will make it difficult for designers to incorporate soil structure interaction in the designs.
Several researchers focused their research work on overcoming the former mentioned challenges in consideration of the soil structure interaction in the seismic design of structures as follows:

- Challenge of nonlinearity and variation of structure and soil parameters

(Park et al., 2007) analyzed the soil-structure interaction of a 6-story structure built on soft soils with uneven soil profile in order to make a design for the structure to resist seismic forces the challenges they faced in the design was the complexity of the soft soil profile and to overcome that the soil structure interaction was performed using finite element method and to reach a uniformly structured stiffness matrix an unaligned mesh generation concept was used as shown in **Fig. 1** and they divided the soil profile into five models one of them is of horizontal flat layers and the other four are of three-layered soft soils with uneven soil profiles as shown in **Fig. 2** and the Gauss quadrature points also used to simplify and accurate the integration of the element with discontinuity of materials also the modified lysmer boundary was adopted to model the boundaries of the soil. The seismic response spectrum of the structure and the soft soil with various profile models was also analyzed. The study showed that using the method proposed in the research the discontinuity of the soil can be presented in a uniform model of the finite element which can lead to an accurate and precise stiffness matrix and that the varying properties and layer models of soft soil effect largely on the seismic response of the soil but this effect is much smaller on the top of the building and that the increase in the softness of soil results lower frequencies of seismic response spectrum. **(Celebi et al., 2012)** made a two-dimensional (2-D) nonlinear finite element model using plaxis software for conducting analysis of the seismic response of soil structure interaction system for a five-storey reinforced concrete building with a basement shown in **Fig. 3.**

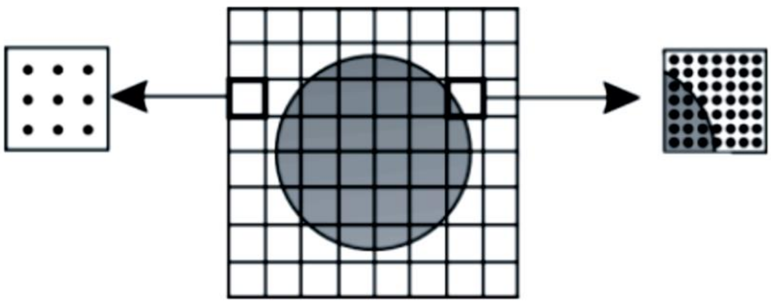

Figure 1. Analysis of finite elements considering discontinuity of material with Gauss quadrature points **(Park et al., 2007)**.

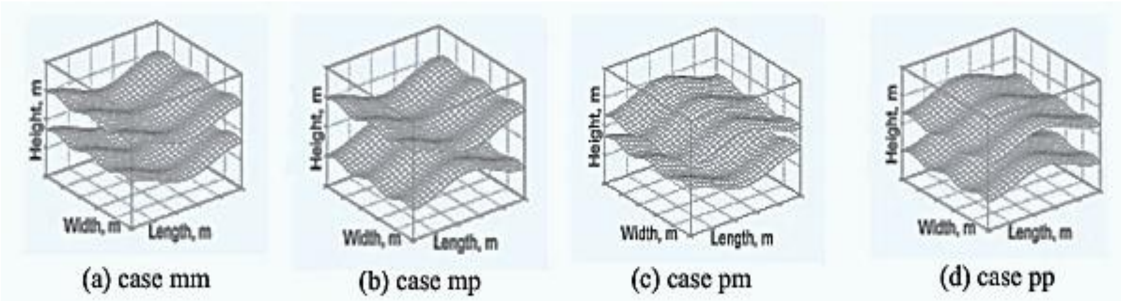

Figure 2. Four types of uneven soil profile models **(Park et al., 2007)**.

The complexity of the analysis is due to the nonlinearity of the stress-strain behavior of the foundation soil under the effect of seismic forces, so the Mohr-Columb model and the Lysmer boundary were used in the analysis. It was found that the effect of soil-structure interaction on the lateral deflections due to seismic forces is greater for structures of fewer stories than slender structures when both supported by loose soil and the increase in the stiffness of the underlying soil increase the role of the seismic motion in increasing seismic response and also the results of the analysis using elastic liner soil model were different from results of analysis using Mohr-Columb model and the effect of the variety of soil characteristics on results of analysis can be ignored as the stiffness of soil and slenderness ratio of structure increases.

(Mekki et al., 2016) extended the N2 Method through accounting for the soil structure interaction in the seismic resistant design of a 3-storey reinforced concrete building, and that was done by replacement of the oscillator in the single degree of freedom model shown in **Fig. 4 (a)** in order to determine the nonlinear behavior of the structure during seismic event. In order to determine the point of performance with considering soil structure interaction shown in **Fig. 4 (b),** the effective period (T) and effective damping ratio (ξ) are presented in Eq. (1) and Eq. (2):

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

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

where k_u = lateral spring stiffness, k_θ = rotational spring stiffness, c_u = lateral spring dashpot, c_θ = rotational spring dashpot, ξ_g = ratio of soil damping, ξ_u = ratio of soil damping in the horizontal mode and ξ_θ = ratio of soil damping in the rocking mode. Curves that determine damage of structures during earthquakes were also generated and the effect of the uncertainty of the seismic loads, damage state of the structure and soil structure interaction was studied. The research results showed the high influence of uncertainties in the seismic loads and the parameters of soil and the slight effect of the uncertainties in the parameters of structures on the nonlinear behavior of the structure also it was found that the structural response during earthquakes not only depends on the dynamic characteristics but also depends on the interaction between the foundation and the surrounding soil.

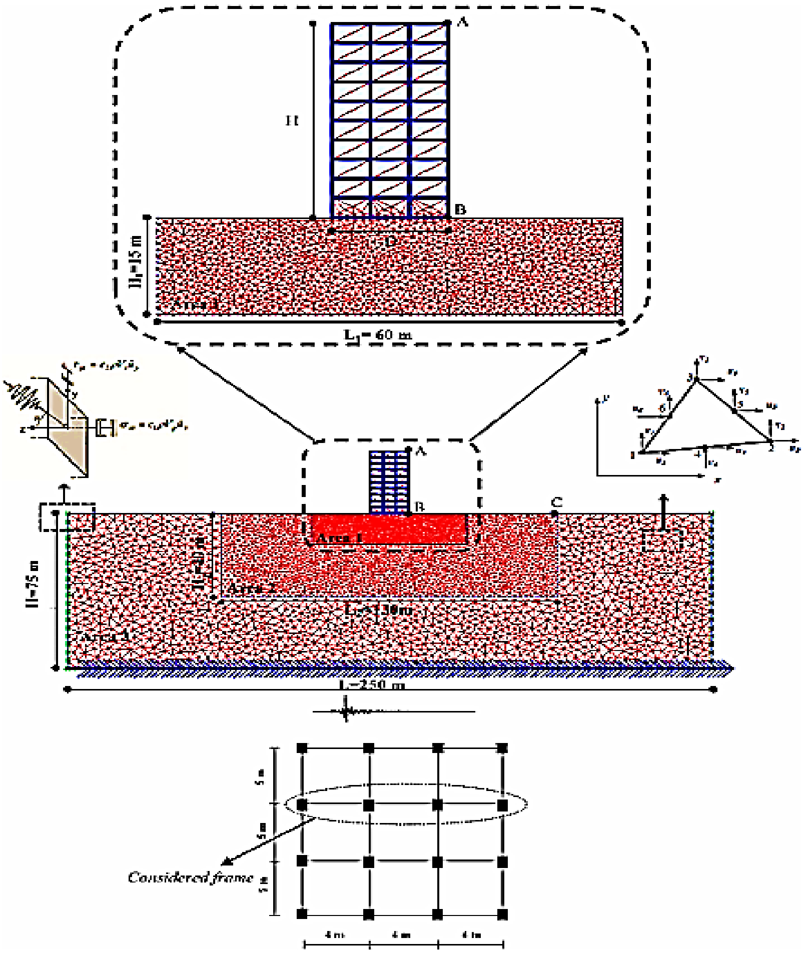

Figure 3. Finite element mesh considered for the soil-structure interaction system **(Celebi et al., 2012)**.

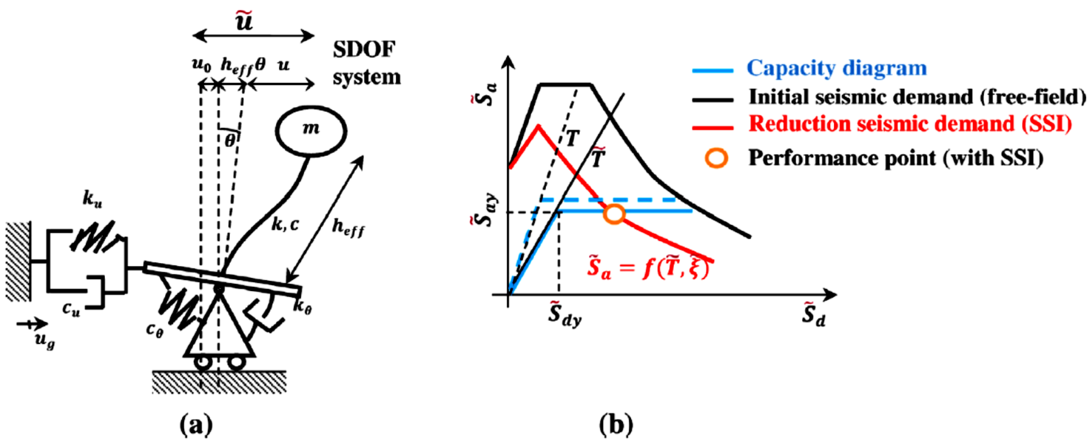

Figure 4. **(a)** Single degree of freedom model **(b)** point of performance **(Mekki et al., 2016)**.

(Long et al., 2021) used the finite-element method to make a two-dimensional static–dynamic numerical analysis to show the effect of seismic forces on three adjacent high-

raised buildings with varying spacing as shown in **Fig. 5** taking into account the nonlinearity in the parameters of soil and structure the numerical analysis was conducted to study the effect of the interaction between the soil and the structure on the seismic response of the structure under the effect of varying ground motion. The results of the study showed that effect of the interaction between the soil and the structure affects the seismic response that occurs between neighbouring structures, especially for buildings spaced in the middle of two adjacent buildings the peak acceleration, maximum shear force on the pile and inter storey drift will be increased as the distance between buildings increases and this effect can be ignored as the ratio between spacing from side to side of buildings to the width of building is equal to or greater than 5 and this effect is more important for adjacent buildings on both sides more than the adjacent building on one side only.
(Mekki et al., 2022) conducted a study using the N_2 method with accounting for soil structure interaction in order to investigate the seismic behavior of a five-storey reinforced concrete building with a square isolated footing with considering the nonlinear behavior of the building and the effect of the soil structure interaction than a sensitivity analysis according to Eq. (3) was done to study the effect of the variation of parameters of concrete, steel and soil on the maximum displacement of the structure due to seismic loads

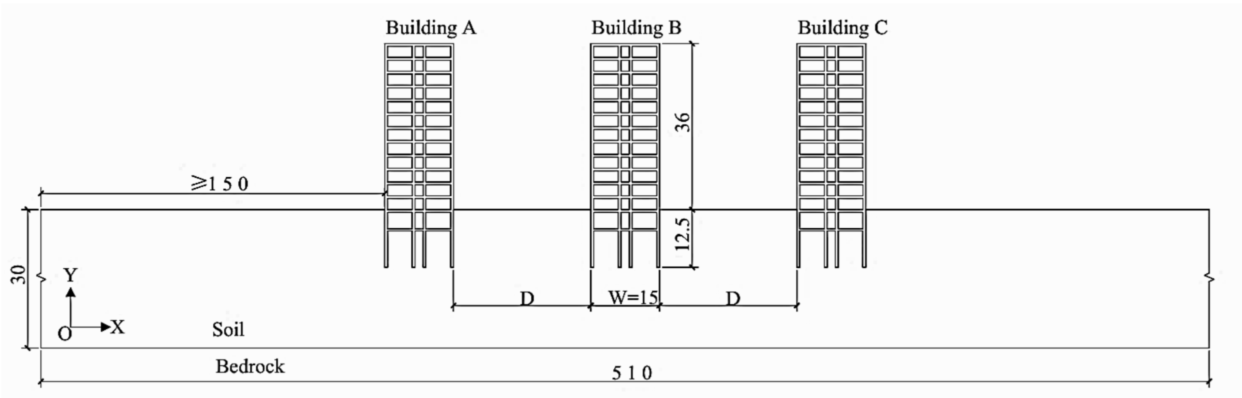

Figure 5. Soil structure interaction model **(Long et al., 2021)**.

$$S = \frac{\partial Y / Y}{\partial X / X} . \quad (3)$$

Where S= sensitivity index, Y= output parameter and X= input parameter. The results of the study showed that the displacement of the structure is very sensitive to the parameters of concrete and steel when increasing the shear wave velocity and the effect of the uncertainties of soil parameters (shear wave velocity and soil damping) has a great effect on the displacement of the structure placed on very soft soil while this effect can be ignored for structures placed on rock soil. A comparison is made between methods used in the previous research to solve challenges of non linearity and variability in soil properties and structural parameters encountered during the dynamic soil-structure interaction analysis and is presented in **Table 1**.
Several studies have been conducted to study the performance of shallow and deep foundations subjected to dynamic loading and investigate the soil-structure response **(Al-Mosawe et al., 2013; Fattah et al., 2017; Al-Jeznawi et al., 2024a).**

Table 1. Comparison between methods of solving the non linearity of soil properties and structural parameters challenge in dynamic soil structure interaction analysis from the previous research.

Auther	**(Park et al., 2007)**	**(Celebi et al., 2012)**	**(Mekki et al., 2016)**	**(Long et al., 2021)**	**(Mekki et al., 2022)**
Type of structure	6-storey structure	5-storey reinforced concrete building	3-storey reinforced concrete building	Three adjacent high-raised building	5-storey reinforced concrete building
Problem encountered in analysis	Soft soil with uneven and complex soil profile	Non linearity of the stress-strain behavior of soil	Uncertainties in soil structure parameters and seismic loads	Non linearity in soil and structure parameters	Variability of soil, steel and concrete on the seismic response
Method of analysis	Finite element analysis	Two dimentional finite element analysis	N2 method with accounting soil structure interaction	Finite element analysis	N2 method with accounting soil structure interaction
Method of solving the analysis problem	Uniform stiffness matrix by using unaligned mesh generation and gauss quadrature points for accurate integration of material discontinuity	Mohr Columb model and the lysmer boundary used in the analysis	Replacement of the oscillator in the single degree of freedom model and determining the performance point	Two-dimensional static - dynamic numerical analysis	A sensitivity study was done to show the effect of variability in parameters of soil, steel and concrete on the seismic response
The research results	Uniform and accurate stiffness matrix and analysis of the seismic response of the structure	Accurate seismic analysis, soil non linearity ignored upon increasing soil stiffness and slenderness ratio	High effect of uncertainties in soil parameters and slight effect of structure parameters on the seismic response	Effect of soil structure interaction on the seismic response especially for buildings spaced in the middle	The effect of the variability in soil properties can be ignored in the case of rock soil

3.3.1 Challenge of the High Cost

(Farfani et al., 2015) Used two kinds of data-based soil structure interaction methods (artificial neural network method and support vector machine method) that were based on mathematical models analysed using neuro solution software in order to make a seismic analysis of soil-pile-structure systems, the input data of both data-based methods was based on results of experimental work of soil model for soil pile system and the results of the two data based methods were compared with the results of the finite element analysis of the same soil pile model.it was found that both artificial neural network method and support vector machine method can predict the soil structure interaction and prediction of dynamic properties with more accuracy than finite element method and in much less time and cost and that support vector machine worked better than artificial neural network method.

(Badry and Satyam, 2016) made dynamic loading analysis including the soil structure interaction effect of an L-shape 11-storey building supported by a pile group foundation and subjected to seismic loading shown in **Fig. 6** by using the equivalent pier method shown in **Fig. 7** which represents the group of the pile as equivalent one pier of modified diameter and young modulus the results of the analysis was compared with the results of the finite element analysis including soil structure interaction of the pile group foundation of the same L-shape building. The results of the study showed that the equivalent pier method is acceptable and provides simplicity and reduction in the complexity of soil structure interaction modelling and helps in the reduction of the computational cost and time and can be used for different types of soils and under different ground motions.

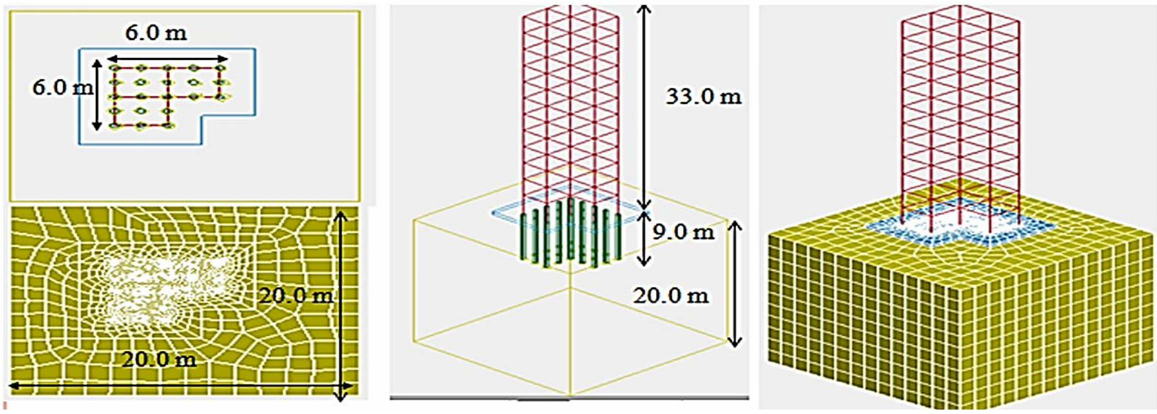

Figure 6. Soil–pile-structure systems considered in the analysis **(Badry and Satyam, 2016)**

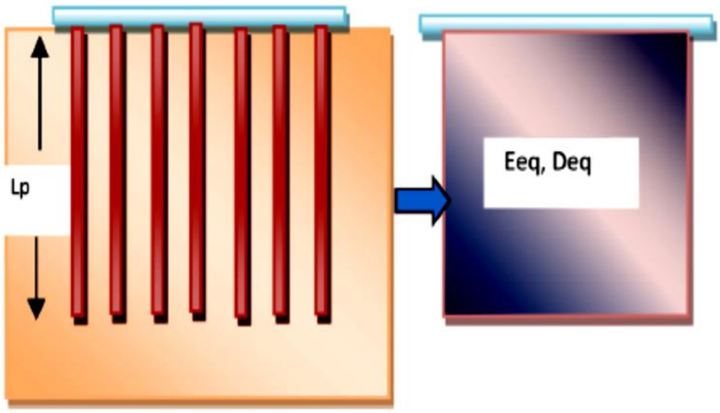

Figure 7. Equivalent pier method concept **(Badry and Satyam, 2016).**

(Choi and Jung, 2020) Conducted soil-structure interaction analysis to determine the seismic response of Nuclear Power Plant using multi-step method considering uncertainty of properties of 30 Soil profiles, soil-structure interaction analysis is conducted by transformation of frequency domain into a time domain response using a model of sway rocking response, the spectrum which was obtained by using multi-step soil-structure interaction analysis method was compared with in-structure response spectrum obtained using a widely used software for the analysis of soil structure interaction and it was found that the multi-step method is numerically verified and the soil structure interaction analysis is expected to be conducted in short computational time.

(El-Hoseiny et al., 2021) Conducted soil structure interaction three-dimensional analysis on seismic response of moment-resisting frames multi-story buildings built on soil with nonlinear conditions with nonlinearity in shear wave velocities, shear moduli and ground motion, using ABAQUS software as shown in **Fig. 8.** The Mohr Columb Model was used to model the soil nonlinearity and the results of the analysis were compared with two-dimensional models of the same buildings. The research results showed that the use of ABAQUS software gives accurate results when compared to analysis using two dimensional models and that decreasing the shear wave velocity and shear modulus of the soil decreases the base shear forces. Therefore, the using of ABAQUS software for the soil structure interaction assures the safety and economy of the seismic analysis of multi-storey buildings. A comparison is made between methods used in the previous research to solve the challenge of the high cost of dynamic soil structure interaction analysis and is presented in **Table 2.**

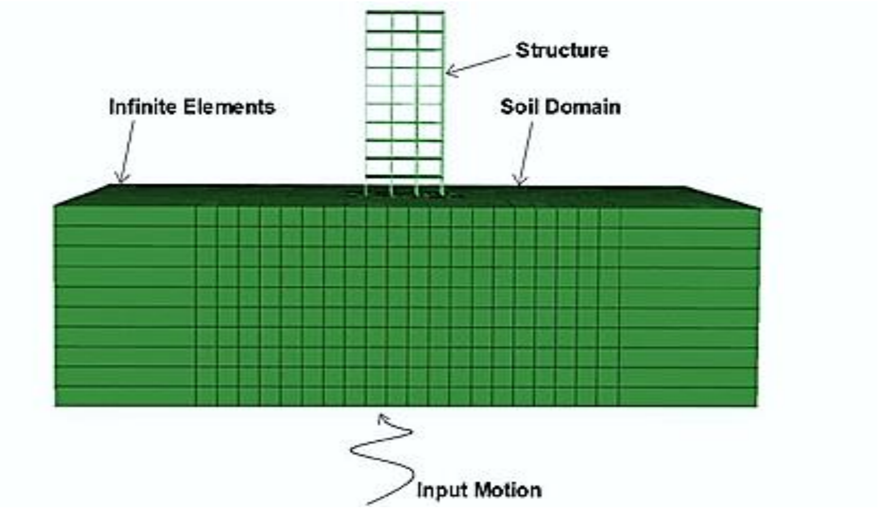

Figure 8. ABAQUS three-dimensional Numerical Model **(El-Hoseiny et al., 2021)**.

3.3.2 Lack of Availability of Standards and Guidelines Challenge

(Anand and Kumar, 2018) made a study in order to add soil structure interaction in structural analysis and the seismic codes guidelines for the selection of the appropriate approach. It was found that only the(ASCE 7-16) standard gives guidelines for the use of soil structure interaction in the analysis and design of structures in contrast all other standards showed circumstances for conducting the soil structure interaction analysis in design practice. Therefore, there is a need to establish guidelines to ensure the inclusion of soil structure interaction in regular design practice.

(Awchat et al., 2022) Showed the effects of soil structure interaction on the seismic response of structures and the various methods to solve soil structure interaction problems and their provisions are mentioned in different International Seismic Codes and found that a lack of detailed guidelines considering soil structure interaction effects in the Indian Seismic code and there is a need to add these guidelines into the Indian Seismic code.

Table 2. Comparison between methods of solving the high-cost challenge in dynamic soil structure interaction analysis from the previous research.

Author	(Farfani et al., 2015)	(Badry and Satyam, 2016)	(Choi and Jung, 2020)	(El-Hoseiny et al., 2021)
Type of structure	Soil model of soil-pile structure system for single piles and pile groups	L-shape 11-storey building supported by a pile group	Nuclear Power Plant	Moment-resisting frames multi-story buildings
The problem encountered in analysis	High cost of finite element analysis including soil-structure interaction	High cost of finite element analysis including soil-structure interaction	High cost and complexity of soil structure analysis and non-linearity of soil	Complexity of soil structure analysis due to the variability of soil and ground motion
Method of analysis	Data-based soil structure interaction methods	Finite element method	Multi-step method	Finite element method
Method of solving analysis problem	Artificial neural network method and support vector machine method with input data taken from soil model	Equivalent pier method	Transformation of frequency domain into a time domain response using a model of sway rocking response	Mohr Columb Model was used to model the non-linearity of soil in ABAQUS software
Research results	The support vector machine method worked better than the artificial neural network method but both worked better than the finite element method and in less cost.	The equivalent pier method provides simplicity in modelling soil structure interaction at less cost	Multi-step method analysing soil structure interaction in less time	ABAQUS software can analyse soil structure interaction for seismic analysis in a more economical way

4. CHALLENGES OF STATIC SOIL STRUCTURE INTERACTION

Static soil-structure interaction can be defined as the interaction between soil and the foundation of a structure due to static loads acting on the structure **(Kunnath, 2020)**.
Some of the static soil structure interaction challenges are:

4.1 The Nonlinear Behavior of the Soil

This is the major challenge in static soil structure interaction that makes the modelling and analyzing process a difficult task.

4.2 Uncertainty

This often occurs in the soil parameters, the modeling parameters, and the condition of loading and that makes it hard to make an exact prediction of the behavior of the soil-structure system.

Several research had been made by researchers in order to overcome the static soil structure interaction challenges, some of these researches are:

(Kralik, 2006) Conducted a study on the influence of uncertainty in soil and groundwater conditions on the structural analysis of raised buildings including the effect of soil structure interaction by using the finite element method. The method of Response Surface was used in the study and its function of approximation is presented by Eq. (4) as follows:

$$\hat{Y} = c_o + \sum_{i=1}^{NRV} c_i X_i + \sum_{i=1}^{NRV} \sum_{j=1}^{NRV} c_{ij} X_i . X_j \tag{4}$$

where C_0 = constant member index, C_i = linear member index and C_{ij} = quadratic member index the function of approximation was solved by using the ANSYS program, **Fig. 9** present the sequence diagram used in constructing the model in ANSYS program and make probabilities of failure of structure. Based on the results it was found that the method of Response Surface is effective more than other methods if the number of input variables is less than 8 and that by using method of Response Surface a modification in the design of the structural system of the high raised building was done.

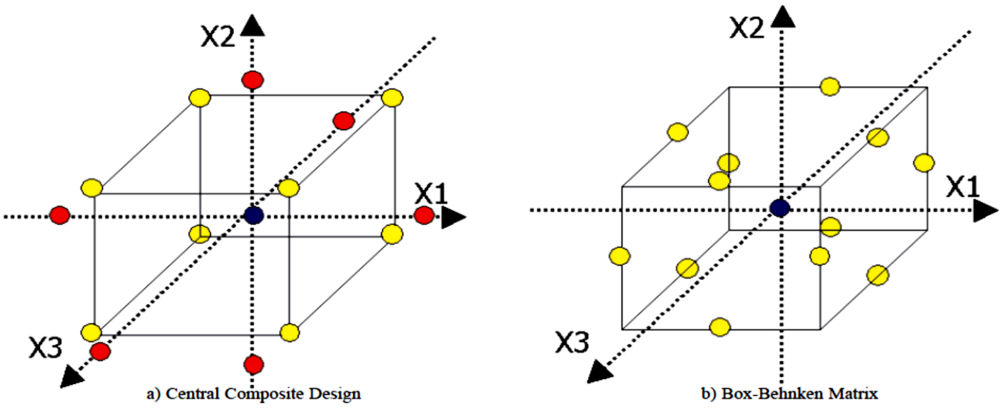

Figure 9. Sequence diagram used in constructing the model in ANSYS program and make probabilities of failure of structure **(Kralik, 2006)**.

(Dang and Meguid, 2011) analysed the quasi-static soil structure interaction problems involving nonlinear soil properties and large deformations through finite–discrete element method to assess the effects of soil loss at the crown of the tunnel on the stresses in the tunnel lining and the rest of the tunnel domain was analysed using finite element method. The analysis of moment and shear forces around the tunnel using previous methods was presented by the numerical results using Plaxis-tunneling 3-Dimentional software shown in **Fig. 10** that was made with the adopting of mohr columb model with nonassociated flow rule and the results were found to be well agreed and provides speed in computations compared with the analysis made with finite element only. Therefore, the combined use of discrete and finite element analysis is advantageous for making an analysis of difficult problems of soil–structure interaction under quasi-static conditions.

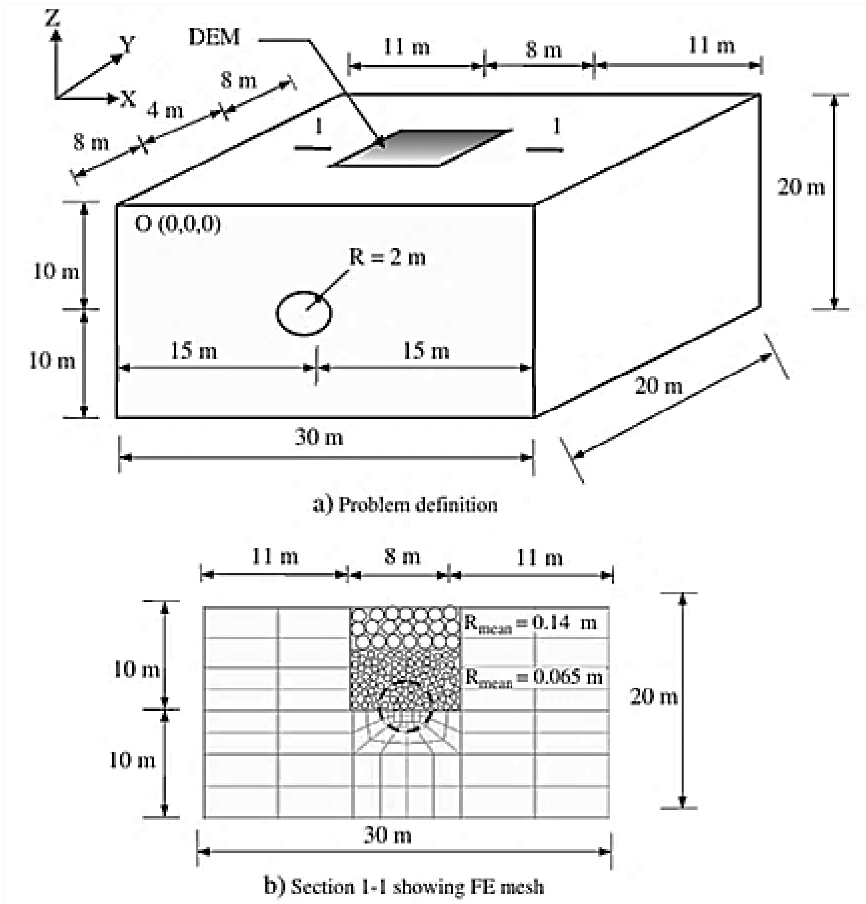

Figure 10. Finite element and discrete element mesh for tunneling using plaxis 3 D software **(Dang and Meguid, 2011)**.

(Dalili et al., 2013) made a review of the methods for the modelling of the static soil foundation systems and the finite element methods used for the static soil structure interaction analysis. The results of the study showed that winkler method is a simplified approach that can be used for the traditional analysis of foundations and it is not enough for accurate soil analysis, in order to make an accurate design of foundations it is necessary to include soil structure interaction at the beginning of the analysis, the increase in the number of elements modelled and analysed using finite element method produces more accurate analysis results of deformations and forces, the use of interface elements is essential to analyse the conditions between different materials and the use of incremental method for the analysis of soil profiles with nonlinear and non homogenous conditions produces more acceptable and realistic analysis.
(Tradigo et al., 2015) Numerically investigated the complex interaction mechanisms of disconnected piled raft foundations in which the pile raft is separated from the underlying piles by a layer of soil through using 3 dimentional finite elements analysis, with considering soil nonlinearity and compared the results of analysis with the 3 dimentional finite element analysis of connected piled raft foundation. The results showed that increasing the gap between the raft and piles in disconnected piled raft aied in decreasing settlement and stiffness efficiency (structural strength) therefore the 3 dimentional finite element analysis

is essential for accurately balancing between structural strength and the acceptable settlement but it was found that the complicated analysis for disconnected piled raft require high costs for large rafts with high numbers of piles.

(Bezih et al., 2015) studied the effect of the soil structure interaction on the probability of failure of reinforced concrete bridges by taking into consideration the nonlinarity in soil properties. The soil structure interaction was modelled using a mechanical model of continuous reinforced concrete beam on nonlinear elastic soil as shown in **Fig. 11** and the model was solved numerically by finite element model in MATHLAB software. Results of the study showed that the soil structure interaction affects the behavior of reinforced concrete bridges and the safety of these bridges are greatly affected by the nonlinerity of soil properties.

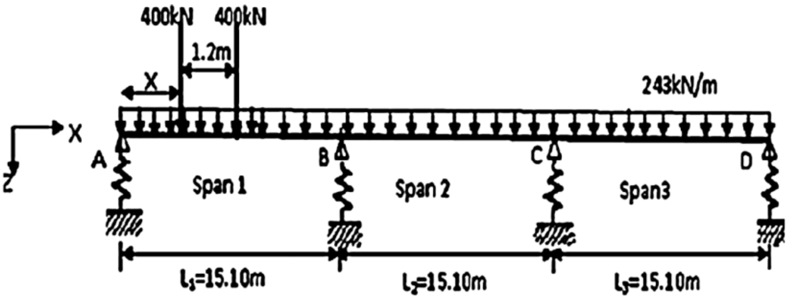

Figure 11. Mechanical model of the reinforced concrete bridge **(Bezih et al., 2015)**.

(Seguini and Nedjar, 2016) investigated the effect of nonlinearity of soil properties and the soil structure interaction on the behavior of buried pipes through making numerical modelling by finite element analysis of the pipeline as a non-linear long beam resting on elastic linear soil of k_{soil}= modulus of subgrade reaction of soil as shown in **Fig. 12** and according to von Karman Eq. (5) as follows:

$$E_p I_p \frac{d^4 w_0}{dx^4} - \frac{3}{2} E_p A_p \left(\frac{dw_0}{dx}\right)^2 \left(\frac{d^2 w_0}{dx^2}\right)^2 + p(x) = q(x) \tag{5}$$

where E_P = young modulus, I_p = moment of inertia, A_p = pipe section, q(x) = distributed load, p(x) = soil reaction, u_0= axial displacement and w_0 = transverse displacement, the numerical modelling was done by using the MATHLAB program to make nonlinear analysis for the buried pipelines. The results of the study showed that the increase of the soil coefficient of subgrade reaction will decrease the deflection bending moment and the shear force of the pipelines and that taking into account the variability of soil properties will give higher and more accurate values of pipelines defections and that will result in a safe and economical design of pipelines.

(Franza et al., 2021) Proposed a two-stage new model for interaction between soil and pile (COMPILE) shown in **Fig. 13** that takes into consideration the effect of non-linear of load transfer mechanism, layering of soil and yielding of soil for both single piles and pile groups at two stages the first stage before tunnelling where piles are subjected to vertical loads only and after tunnelling where piles are affected by loads from tunnelling the model was numerically solved using finite element method and computed using MATHLAB program and the results was compared with the results of other non-linear simpler models.

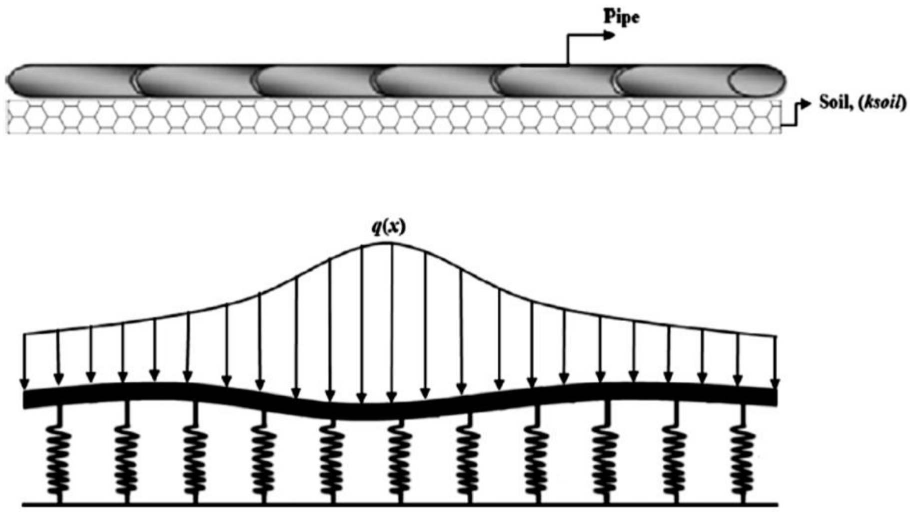

Figure 12. The model used for numerical analysis considering the pipe resting on elastic soil **(Seguini and Nedjar, 2016)**.

It was found that the (COMPILE) model can analyze single piles and pile groups subjected to vertical loads and affected by tunnelling and predict better analysis of variation of settlement and forces and that the pile raft aids in decreasing the surface settlement induced by tunnelling and increase the distress of foundation because of tunneling and its necessary to apply soil interaction analysis to models to obtain better results

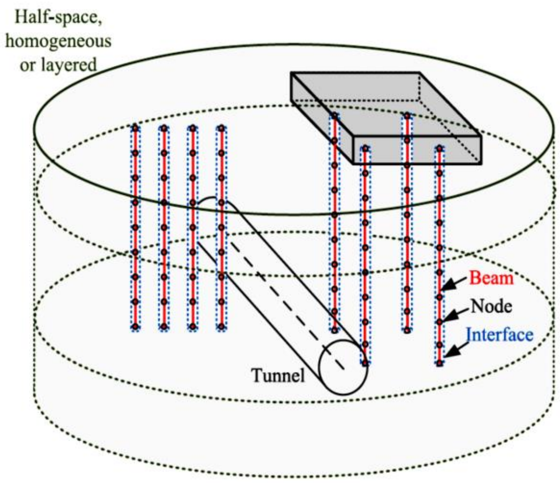

Figure 13. Skectch of COMPILE Model **(Franza et al., 2021)**.

A comparision is made between methods used in the previous researches to solve challenge of non linearity and uncertainty in soil properties that encountered during the static soil structure interaction analysis and is presented in **Table 3**.
In addition, other studies conducted to investigate the soil structure problem under static loading **(Al-Mosawe et al., 2013; Al-Mosawe et al., 2021; Al-Jeznawi et al., 2022a; Al-Jeznawi et al., 2022b; Al-Jeznawi et al., 2022c; Hasan and Al-Saidi, 2022).**

Table 3. Comparison between methods of solving the nonlinearity and uncertainty of soil properties challenge in static soil structure interaction analysis from the previous research.

Author	Structure Type	Problem in analysis	Method of analysis	Method of solving analysis problem	Research results
(Kralik, 2006)	High raised building	Uncertainty in soil and ground water conditions	Finite element method	The response surface method and its function of approximation were solved using the ANSYS program to make probabilities of failure of the structure	The response surface method is effective if the number of input variables is less than 8 and it helps in improving the design of high-raised buildings
(Dang and Meguid, 2011)	Tunnel	Non linear soil properties	Finite–discrete element and finite element method	The crown of the tunnel was analysed using the finite discrete element and the rest of the tunnel domain was analysed using finite element method	Combined use of discrete element and finite element methods provide speed of computation of soil structure interaction analysis
(Tradigo et al., 2015)	Disconnected piled raft foundation	Soil non linearity and gap between pile raft and piles	Finite element method	3 dimentional finite element analysis with accounting soil non linearity	The complicated analysis for disconnected piled rafts require high costs for large rafts with high numbers of piles
(Bezih et al., 2015)	Reinforced concrete bridge	Non linear soil properties	Finite element method	A mechanical model of the continuous reinforced concrete beam on nonlinear elastic soil was used then it was solved numerically	Soil structure interaction affects the behavior of reinforced concrete bridges their safety is affected by non-linearity of soil properties
(Seguini and Nedjar, 2016)	Buried pipe	Soil non linearity	Finite element method	Numerical modelling of the pipeline as a non linear long beam resting on elastic linear soil	Taking into account the soil nonlinearity and soil structure interaction will result in a safe and economical design of pipelines
(Franza et al., 2021)	Single piles and pile groups	Non linear soil properties and tunneling	Finite element method	Two-stage interaction model between pile and soil before and after tunneling	The two stage model can predict the effect of soil structure interaction on the behavior of piles before and after tunneling

5. METHODS OF OVERCOMING CHALLENGES IN SOIL STRUCTURE INTERACTION

5.1 Improved Modelling Techniques

The challenges in soil structure interaction can be overcome by improving the existing models such as nonlinear static and dynamic models, the sensitivity of structure and soil properties, and hybrid models in which part of the analysis is solved numerically while another analysis is based on the experimental results and these models have proved to solve the complexity in the analysis of soil-structure interaction problems **(Hashash and Park, 2001; Albusoda and Salem, 2016; Al-Saidi et al., 2016; Almashhadany and Albusoda, 2019, Hussein and Albusoda, 2021; Al-Jeznawi et al., 2022a; Alhalbusi and Al- Saidi, 2023; Al-Jeznawi et al., 2024a; Al-Jeznawi et al., 2024b; Noman and Albusoda, 2024).**

5.2 Advanced Construction Technologies

These technologies include ground improvement techniques and isolation systems. The ground improvement techniques aim to strengthen the soil to minimize the soil structure interaction effect on the behavior of the structure. Soil improvement techniques include soil stabilization, grouting, and compaction **(Sarsam et al., 2011; Sarsam et al., 2016a; Dhakar and Jain, 2016; Sarsam et al., 2016b; Sarsam et al., 2017a; Sarsam et al., 2017b; Abd Al-Kaream, 2020; Al-Saidi et al., 2022; Hasan and Al-Saidi, 2024)** while isolation systems help in minimizing the influence of the seismic forces transmitted from the ground to the structure **(Çerçevik et al., 2020; Loveridge et al., 2020).**
Soil improvement aids in strengthening the ground and making it resistant to deformation under loads **(Das, 2010)** some of the soil improvement techniques are:

a- Dynamic compaction: This technique involves the strengthening of the soil by a free fall of a high-energy impact load. This method helps increase the density of the soil thus increasing the resistance to seismic loads **(Bo et al., 2008**; **Brule and Duquesnoy, 2016)**.
b- Vibro compaction in which the loose granular soil is compacted by the insertion of a vibrating probe and the soil becomes dense reducing the risk of liquefaction during earthquakes **(Grabe, 2017**; **Gouw, 2022)**.
c- Geosynthetic reinforcements include geocells, geotextiles and geogrids which reinforce the soil and increase its strength. **(Al-Mosawe et al., 2008; Al-Mosawe et al., 2010, Das, 2010; Sarsam et al., 2013; Bachay and Al-Said, 2022; Mohammed and Al-Saidi, 2023; Bachay and Al-Saidi, 2024; Mohammed and Al- Saidi, 2024).**
d- Deep soil mixing: in this technique, the soil is injected and mixed with the soil by special deep mixing augers thus increasing the strength of the soil and its resistance to seismic forces **(Alhamdi and Albusoda, 2021)**.

5.3 Improved Foundation Design

The use of a pile and a raft helps in minimizing the influence of soil structure interaction as follows:

a- Raft foundations: aids in minimizing the effect of soil structure interaction, especially for weak soils, by distributing the loads on a larger area **(Bazaz et al., 2021)**.
b- Pile foundations: are long slender structural elements that transfer the superstructure loads through the weak or highly compressible soil layers to a deeper stronger and less

compressible soil layer thus reducing the uplift forces caused by the effect of seismic loads **(Das, 2010; Wang et al., 2022)**.

5.4 Design of Structures to Resist Seismic Forces

The design of the earthquake-resistant structures involves making the structure more durable, stiff and deformable in a controlled manner under seismic loading also the use of energy dissipation and base isolation systems for reducing the forces transmitted from the ground to the foundation during earthquakes **(Freddi et al., 2021)**:

a- Energy dissipation systems: that are used to absorb and dissipate the seismic forces transmitted to the structure during earthquakes thus reducing the effects on the structure common types of energy dissipation systems are metallic yield dampers, viscous dampers, and friction dampers **(Freddi et al., 2021; Titirla, 2023)**.

b-Base isolation: this design separates the structure from the ground thus reducing the earthquake forces transmitted to the structure common types are friction pendulum bearings, elastomeric bearings, and sliding bearings **(Matsagar and Jangid, 2008; Shahabi et al., 2020).**

6. CONCLUSIONS

1. The complexity in interaction analysis between structure and foundation has become a complicated matter mostly due to the non-linear behavior of the soil, the finite element method is used to deal with material nonlinearity and non-homogeneity. Famous laws and computational methods were presented to correspond to nonlinearity of soil behavior to show the importance of model application which is vital to the interpretation of numerical analysis.
2. For evaluating the interfacial forces between two mediums interface elements have been used to give a better idealization of interfacial conditions between different mediums.
3. The soil structure interaction has a negligible effect when the foundation is placed on firm soil.
4. The analysis of soil-structure interaction in the event of seismic loading showed that the uncertainties of the soil parameters greatly affect the structural response while the effect of uncertainties of the structural parameters is slight and the effect of the uncertainties of the soil can be ignored upon increasing soil stiffness and slenderness ratio of the structure.
5. The soil structure interaction of adjacent high-rise structures should be totally accounted for in the seismic design of structures especially for structures placed in the middle.
6. There is a need to add guidelines on the implementation of soil structural interaction in seismic codes in order to include it in the regular design practice of structures.
7. It is essential to consider static soil structure interaction analysis to ensure the safe and economical design of structures.
8. The non-linearity and uncertainty of soil properties greatly affect the safety of structures.
9. The improvement of foundation soil will reduce the effects of soil-structure interaction.

Credit Authorship Contribution Statement

Ban H. Al-Khayyat: Writing – original draft, review & editing. Bushra S. Albusoda: Review & editing, Validation. A'amal A. H. Al-Saidi: Review & editing, Validation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared

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تحديات مشاكل تفاعل التربة مع المنشأ – مراجعة

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قسم الهندسة المدنية، كلية الهندسة، جامعة بغداد، بغداد، العراق

الخلاصة

يتناول هذا البحث استعراض البحوث السابقة التي تم إجراؤها لحل تحديات وتعقيدات تفاعل التربة مع المنشأ (soil– structure interaction) الستاتيكي والديناميكي من خلال مناقشة النماذج الحسابية المتقدمة وتطبيقاتها واستكشاف طرق حل تحديات تفاعل التربة مع المنشأ في هندسة الأساسات لتوفير دليل للمجتمع الهندسي من اجل حل تعقيدات تفاعل التربة مع المنشأ. وجد أن التحليل العددي لتفاعل التربة الستاتيكي والديناميكي باستخدام طريقة العناصر المحدودة بمساعدة النماذج الحسابية المتقدمة مثالي للتعامل مع عدم خطية خصائص التربة والمنشأ وظروف التحميل وأن استخدام عناصر الواجهة هو أمر ضروري لإضفاء الطابع المثالي على القوى بين وسطين مختلفين وأنه لا يمكن تجاهل تأثير التفاعل للمباني المجاورة في التصميم الزلزالي في المباني المرتفعة خاصة للمباني التي في المنتصف وتأثير عدم خطية خصائص التربة يمكن تجاهلها في التصميم الزلزالي عند زيادة صلابة التربة ونسبة نحافة المباني وعندما يتم تحسين تربة الأساس. يمكن تقليل تكلفة ووقت التحليل للتفاعل الديناميكي للتربة مع المنشأ باستخدام طريقة الدعامة المكافئة (equivalent pier method) ، ونموذج (Mohr Columb) في برنامج (ABAQUS)، وطريقة متعددة الخطوات وقائمة على البيانات (multi step data based method) ، وهناك حاجة لإضافة إرشادات حول تنفيذ التفاعل الديناميكي للتربة مع المنشأ في الكودات الزلزالية من أجل تضمينها في تعليمات التصميم المنتظمة للمباني. علاوة على ذلك ، وجد أن عدم الخطية وعدم اليقين في خصائص التربة يؤثر بشكل كبير على سلامة المنشآت ومن الضروري النظر في تحليل التفاعل الستاتيكي التربة مع المنشأ لضمان التصميم الآمن والاقتصادي للمباني.

الكلمات المفتاحية: التفاعل الديناميكي للتربة مع المنشأ، طريقة العناصر المحددة، التفاعل الستاتيكي للتربة مع المنشأ.