CONSIDERATION OF SOIL-STRUCTURE INTERACTION DURING STRUCTURAL ANALYSIS

Asaduzzaman*[1] and Souptik Barman Tirtha[2]

[1]*Junior Structural Engineer, Development Design Consultants Limited, Bangladesh,*
e-mail: asaduzzaman04008@gmail.com
[2]*M.Sc. Student (Civil & Geotechnical), Bangladesh University of Engineering and Technology, Bangladesh,*
e-mail: souptik.tirtha@gmail.com

***Corresponding Author**

ABSTRACT

In order to ensure the safety of structures, especially in the case of an earthquake, the interaction between structure and soil is of the utmost importance in both geotechnical and structural engineering fields. While ETABS is being used widely for the modeling of multi-storied buildings, soil elements cannot be designed in ETABS, which limits its ability to provide a complete picture of the behavior of structures, particularly when the effect of soil on the structure is essential to consider. In this paper, analyses have been carried out to determine how the consideration of Soil-Structure Interaction (SSI) during the design of multi-storied buildings can affect the results of the structural analysis. Separate models have been generated based on the same 10-storied framed structure with basement and these models are subjected to the same vertical loads along with lateral loads. While designing the structure in ETABS, different support conditions have been considered to determine the influence of support conditions on the structure. Furthermore, area spring constant is applied for the soil below the mat foundation. A total of three ETABS models are generated considering different support conditions as well as different applications of spring constants to get a proper picture of the changes in the analysis results in ETABS based on the modification of the support condition. In PLAXIS 3D, the mat foundation is assigned as a plate element and the soil surrounding the foundation is modeled based on the Mohr-Coulomb soil model. Deviations have been observed among the results obtained from PLAXIS 3D and ETABS, and these deviations have been documented in tabulated form. These deviations in the results indicate that when interaction between soil and structure is considered, the behavior of the structure changes, which can have a detrimental effect on the usability and safety of the structure.

Keywords: *Soil-Structure Interaction (SSI), Mohr-Coulomb soil model, behavior of structures, PLAXIS 3D, ETABS*

1. INTRODUCTION

While designing and modeling a structure, the whole structure is often divided into two parts, the portion below the Finished Ground Level (FGL), known as Substructure; and the other portion called Superstructure. The substructure contains different structural elements which are surrounded by soil, such as mat foundation, pile cap, piles, footing, etc.; which are used to transfer the load from the superstructure to the soil below. As the substructure and superstructure are connected to each other, the behavior of one affects the behavior of the other. Therefore, it is implausible to consider these two systems to be independent.

Soil-Structure Interaction (SSI) refers to a condition in which the structure stops to behave independently and its behavior gets significantly influenced by the behavior of the soil surrounding it. It is of utmost importance to take SSI into account when we are considering the effect of earthquakes on the structure. Though SSI can cause large deviations in the seismic behavior of the structure, thereby making it imperative to consider it during the design of structures, SSI is rarely implemented during the design of the structure by the practicing engineers in Bangladesh.

The main reason behind not using SSI in the design process of structural elements is the belief that SSI brings a good response to the structure, and neglecting it will only increase the safety margin of the structure (Stewart et al., 1999; Mylonakis et al., 2006; Liu et al., 2020). For this reason, the general practice of structural engineers is to consider the soil below the structure to be rigid, which has negligible influence on the dynamic behavior of the structure above. The consideration of SSI increases the natural time-period of the structure (Ganjavi and Hao, 2012; Wolf and Obernhuber, 1985). Moreover, damping of the structure increases due to radiation damping occurring in the surrounding soil, and the demand for base shear at the foundation decreases (Applied Technology Council, 2020). At the same time, consideration of SSI can complicate the design process and as it is an iterative process, the time required to perform it is higher than just considering no interaction between the structure and the soil beneath it. However, the effect of SSI is not neglected in the case of critical and heavy structures such as nuclear power plants and hydraulic megastructures such as dams, as well as in the case of structures on very soft soils (Finini & Paolucci, 2016; Sharma et al., 2020; Ali et al., 2023). As the fundamental time-period of a structure increases with the consideration of SSI, it can lead to resonance with the soil vibrations during seismic activities, thereby increasing the deflection of the structure significantly (Wani et al., 2022). As the natural period of a structure increases, the requirement for ductility also increases (Finini & Paolucci, 2016). Without providing adequate ductility to address this issue, permanent deformation of the structure can occur, limiting its usability.

The study of SSI in the field of earthquake engineering considers SSI to be a form of seismic excitation, and it is generally considered when SSI can impart a considerable amount of force into the structure. The seismic response of a structure mainly depends on the three interlinked systems, which are the structure, the foundation, and the underlying soil. As the soil has an impact on the dynamic behavior of the structure, the structure also affects the dynamic behavior of the soil surrounding it during seismic activities. The free-field motion of the soil without the presence of structure is much higher compared to the foundation input motion of the soil responsible for the excitation of the structure and its foundation. While considering the SSI, the whole system is to be taken into account to get a better picture of the structure's dynamic behavior during a seismic event. Mortezaee & Akhtarpour (2016) studied the efficacy of using PLAXIS 2D software for the analysis of building frames. In their study, PLAXIS 2D was found to be capable of analyzing building frames and the moments of the structural elements. However, in their study, they only used PLAXIS 2D software without considering the soil-structure interaction. In this paper, PLAXIS 3D software is used to create a model of the structure with surrounding soil profile for the analysis of soil-structure interaction and compare it with the results obtained from ETABS analysis.

1.1 Objectives of the Study

The main objectives of the study are given below:

- Comparison of the deflection values obtained from PLAXIS 3D and ETABS
- Comparison of the story drift values obtained from PLAXIS 3D and ETABS
- Comparison of beam moments
- Determination of the effect of SSI on foundation deformation
- Comparison of the moment values in the foundation along both horizontal axes

2. METHODOLOGY

In this paper, a 10-storied building with one basement has been considered. The height of each floor, including the basement is considered to be 3 meters. A mat foundation of 750 mm thickness is considered at the bottom of the structure.

For the modeling and determination of the seismic behavior of the structure through PLAXIS 3D and ETABS, the required calculations are performed based on the requirements provided in Bangladesh National Building Code (BNBC) 2020. A stepwise description of the methodology is provided below:

- Firstly, a location is considered in Gazipur, Dhaka, which is in Seismic Zone 2.
- A layout of the structure is created for modeling.
- Based on the layout of the structure, models are created in ETABS and PLAXIS 3D.
- For the analysis of soil-structure interaction, the required properties of the soil are considered based on the available literature, and those properties are imparted in the models.
- Analyses are performed in ETABS and PLAXIS 3D.
- The results of the analyses are tabulated as necessary, and other essential data are taken as illustrations from the respective software.
- The results are compared and discussed to determine how the consideration of SSI can cause deviations in the ways a structure behaves.

2.1 Earthquake Load

In this paper, for consideration of the lateral loads, only the lateral loads along the X-axis are calculated. The total seismic lateral force at the base level (base shear V) is the sum of lateral forces (F_x) induced at different floor levels. These forces are calculated using the following equation (1):

$$F_x = \frac{W_x h_x^k}{\sum_{i=1}^{n} W_i h_i^k} \quad (1)$$

Where,

F_x= Part of base shear force induced at level x, W_i and W_x = Part of the total effective seismic weight of the structure (W) assigned to level i and x respectively, h_i and h_x = the height from the base to level i and x respectively, n = number of stories, and k is a constant whose value ranges from 1 to 2 depending on the time-period of the structure.

The time-period (T) of the structure is determined through the following equation (2):

$$T = C_t (h_n)^m \quad (2)$$

Where, Ct & m are numerical coefficient to determine building period.

2.2 General Overview of the Model

For the structural frame, the spacing of the grid lines is taken as 6000 mm – 3000 mm – 6000 mm in both horizontal axes. The columns are drawn considering a 450 mm x 450 mm cross-section, and the structural walls are thought to be of 250 mm thickness. The basement wall is also designed with a thickness of 250 mm. In the models, no stiffness modifiers have been applied for the structural elements. The mat foundation below the structure has an area of 16 m x 16 m.

The vertical live loads are assigned as line loads of 30 kN/m on all the beams except for the roof beams. The seismic load is assigned as lateral point loads at the beam-column joints. The vertical dead loads are due to the weight of the structural elements.

2.3 Description of ETABS Models

For the ETABS model, the modulus of spring constant of the soil is considered to be 8000 kN/m/m^2. A total of three ETABS models are created for the analysis. In the first model, soil spring constant is considered only in the vertical direction. In the second model, instead of applying spring constants below the mat foundation, fixed supports are provided at the location of the joints in the base to determine how the deflection behavior and moments of the structure change due to this consideration. This consideration is analyzed as in the professional practices in Bangladesh, generally the superstructure is designed considering fixed supports at the base, and then from the reactions at the base from ETABS, CSI SAFE software is used to design the foundation. As the foundation is a mat foundation, it is possible for us to consider supports to be fixed at the base if necessary for analysis. It is due to the fact that the mat foundation has the capability of restraining all the translations and rotations of the structure due to its high level of rigidity compared to other foundation systems. A layout of the structure is provided in Figure 1.

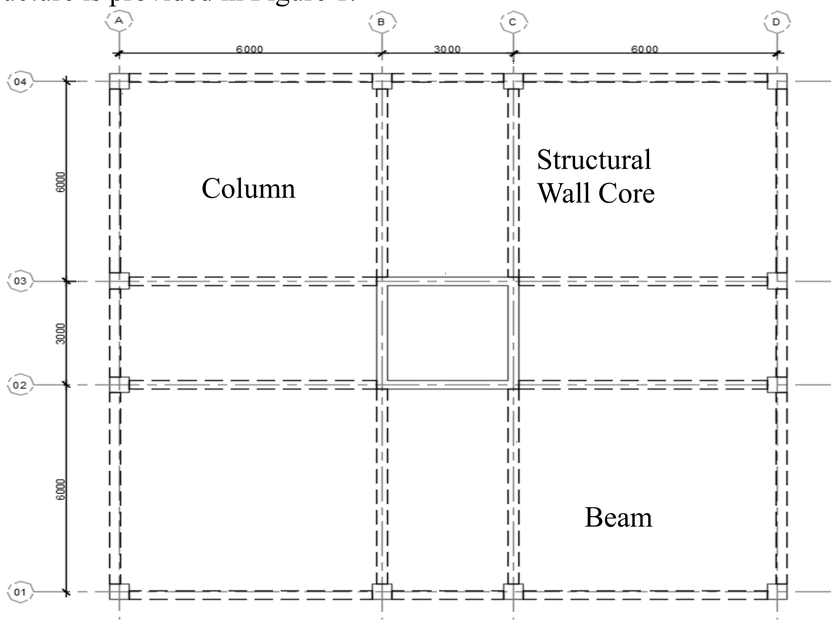

Figure 1: Layout of the Structure

In the third model, 10% of the soil spring constant value in the vertical direction is applied in both the lateral directions to find out how it can affect the moment profile at the base. In the ETABS models where soil spring constant is applied below the foundation, horizontal restraints are added at three corners of the base to prevent movement of the mat foundation.

2.4 Description of PLAXIS 3D Model

For the PLAXIS 3D model, a soil area of 50 m x 50 m with a depth of 30 m is considered. Groundwater level is provided at 1.5 m below the ground surface. The basement is designed to be 3 m below the ground level. The foundation is modeled as a plate element of 750 mm thickness. For the meshing of the soil profile, a finer mesh is used over an area of 21 m x 21 m with 6 m depth below the foundation. Over the rest of the soil volume, coarse mesh is used to reduce the time required for analysis. Figure 2 illustrates the model of the total system, including the surrounding soil, structure, and substructure as created in PLAXIS 3D.

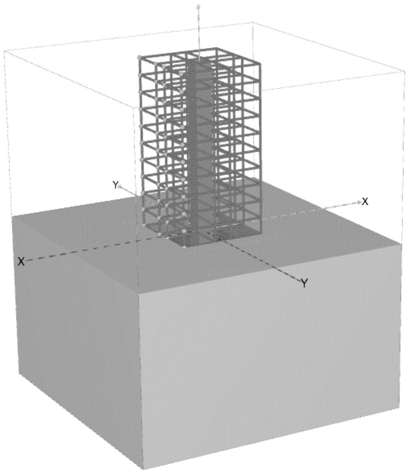

Figure 2: Structure with surrounding soil in PLAXIS 3D

A constitutive model of the soil is created considering perfect linear elastic-plastic behavior of the soil (Mohr-Coulomb Model) based on the properties of the soil provided in Table 1. The beams and columns are modeled as linear elastic, while the mat and walls are also modeled as linear elastic with a Poisson's ratio of 0.2. The stiffness of the soil can also be measured with the effective soil parameters provided in Table 1.

Table 1: Properties of Soil for PLAXIS 3D

Soil	**Elastic modulus (kPa)**	**Undrained cohesion (kPa)**	**Density (kN/m^3)**	**Poisons ratio**
Silty Clay	45000 + 5000*z	50 + 5*z kPa	17.5	0.3

Where, z is the depth of the soil layer from the top in meters.

3. ANALYSIS RESULTS AND DISCUSSIONS

The findings of the analyses for the SSI are provided and discussed in this section. The findings include the deflection and drift values of the building frame, moments in the beams, the deformation profile of the foundation, and moments of the foundation along the two horizontal axes (X-axis and Y-axis).

3.1 Comparison of the Deflection Values

In the first step, the obtained deflections from PLAXIS 3D and ETABS are tabulated in Table 2 to see the differences among the obtained values. The deflections are calculated in the direction of the X-axis, as lateral earthquake forces are applied in the X-axis direction.

Table 2: Deflection of the building due to lateral load

Level	**Location**	**Value from PLAXIS 3D**	**Value from ETABS (Soil as Area spring)**	**Value from ETABS (Fixed Support)**
		mm	mm	mm
1F	middle	13.42	9.41	3.44
	corner	8.69	9.32	3.75
5F	middle	54.11	37.33	20.12
	corner	56.81	42.06	25.20
roof	middle	111.5	73.03	42.10
	corner	108.3	71.37	40.78

From the values in Table 2, it can be observed that the maximum amount of deflection is seen in the PLAXIS 3D model. In the PLAXIS 3D model, a constitutive soil model is created with the model of the structure for the proper analysis of SSI. As the lateral loads are working on the structure, the movement of the foundation is occurring. Since the structure is stiffer compared to the soil in this case, the rotation and translation of the foundation are taking place relative to the free-field motion of the soil, adding to the total displacement of the structure. This phenomenon leads to an increase in the fundamental period of the structure (Applied Technology Council, 2020).

In the case of the ETABS models, the deflection of the structure is measured without any consideration for the movement and behavior of the surrounding soil. As a result, the amount of deflection is much lower compared to the PLAXIS 3D model, indicating a lower fundamental period for the structure. Furthermore, from Table 2 data, it is evident that considering a fixed support reduces the total deflection of the structure.

3.2 Drift Comparison

To determine the effect of SSI on the drift characteristic of the structure, the drift ratios at different levels of the structure are tabulated in Table 3. Similar to the measurements of deflection, the drift ratios are calculated in the direction of the X-axis for the lateral earthquake load along the same axis. After the calculation of the drift ratios, the drift ratios are multiplied by the deflection amplification factor, C_d as required by BNBC 2020. In this study, the structure is considered to be built on soil type SC with a dual system, as it contains both shear wall and concrete moment-resisting frame. The seismic design category is C for this structure based on the requirements of BNBC 2020. From BNBC 2020, the deflection amplification factor for the structure is found to be 5, and the drift ratios of the structure are multiplied by the amplification factor to determine if the drift of the structure is within the limit provided by BNBC 2020 which is 0.02 for this structure.

Table 3: Drift ratio along the X-axis due to lateral load

Level	Location	Value from PLAXIS 3D		Value from ETABS (Soil as Area spring)		Value from ETABS (Fixed Support)	
		Drift Ratio	Drift Ratio*C_d	Drift Ratio	Drift Ratio*C_d	Drift Ratio	Drift Ratio*C_d
1F	middle	0.0028	0.0140	0.0018	0.0089	0.0008	0.0040
	corner	0.0026	0.0130	0.0022	0.0109	0.0013	0.0063
5F	middle	0.0038	0.0190	0.0025	0.0126	0.0016	0.0078
	corner	0.0039	0.0195	0.0026	0.0132	0.0017	0.0085
roof	middle	0.0037	0.0185	0.0022	0.0108	0.0012	0.0062
	corner	0.0025	0.0125	0.0013	0.0063	0.0004	0.0018

From the tabulated values in Table 3, it is axiomatic that the consideration of SSI increases the drift ratios of the structure by a significant level. The minimum amount of drift ratio is found in the case of fixed support condition, as it has a much greater capacity of limiting the deflection of the structure. Nevertheless, the drift ratios are still within the limit provided by BNBC 2020, even in the case of PLAXIS 3D.

3.3 Comparison of Beam Moments

To determine seismic requirements for the structure, the moments in the beams are tabulated in Table 4. From the obtained values, it is obvious that in this case, the consideration of SSI has decreased the moments in the structural members, as the moments found in PLAXIS 3D are much lower compared to the moment values from ETABS models. Here, the exclusion of SSI would make the design of the structure more conservative, as found in many literature (Stewart et al., 1999; Mylonakis et al., 2006; Liu et al., 2020).

Table 4: Measured Beam Moments

Level	Location	Value from PLAXIS 3D		Value from ETABS (Soil as Area spring)		Value from ETABS (Fixed Support)	
		Hogging Moment (kN-m)	Sagging Moment (kN-m)	Hogging Moment (kN-m)	Sagging Moment (kN-m)	Hogging Moment (kN-m)	Sagging Moment (kN-m)
1F	middle	155.9	51.62	234.08	76.17	225.68	76.30
	edge	160.2	54.14	175.71	93.78	171.28	92.14
5F	middle	168.5	52.7	327.73	123.85	323.88	123.15
	edge	168.4	53.27	168.67	84.24	165.68	83.46
Roof	middle	67.48	64.40	188.54	112.63	186.32	111.84
	edge	49.97	20.87	35.83	21.43	35.98	21.63

Also, from Table 3, it can be noted that the replacement of the supports at the base from soil as area springs to fixed supports has no significant impact on the beam moments in this case. It is to be expected, as considering fixed support mainly decreases the seismic demand of the structural columns and shear walls, without any significant impact on the moments to which the beams are going to be subjected.

3.4 Comparison of the Deformation Profiles below Mat Foundation

Settlement below the foundation level is found to be non-uniform for both ETABS and PLAXIS 3D models. In the case of the PLAXIS 3D model containing the 50 m x 50 m soil area section, illustrated in Figure 3, a maximum settlement of 9 mm is observed, located at the second half portion of the foundation from the direction of applied lateral force. It is also noticeable that the position of the maximum settlement is at the lift core wall edge. The downward movement of the soil below the foundation level is causing an upward movement in the soil volume outside the perimeter of the foundation. Approximately 2 mm upward movement is noticed near the edges of the 50 m x 50 m section of the soil.

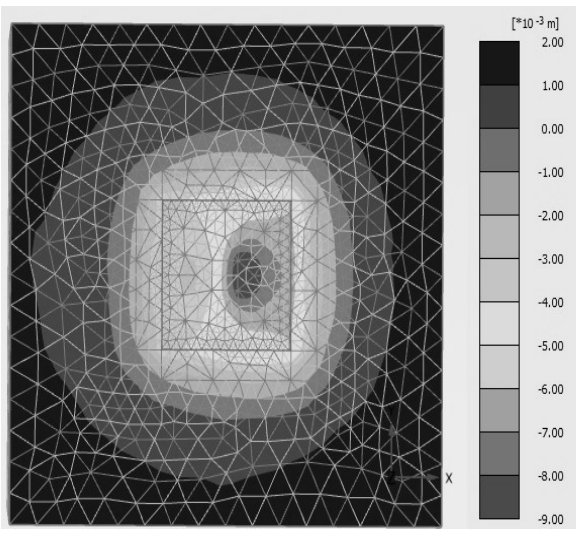

Figure 3: PLAXIS 3D Deformation Profile

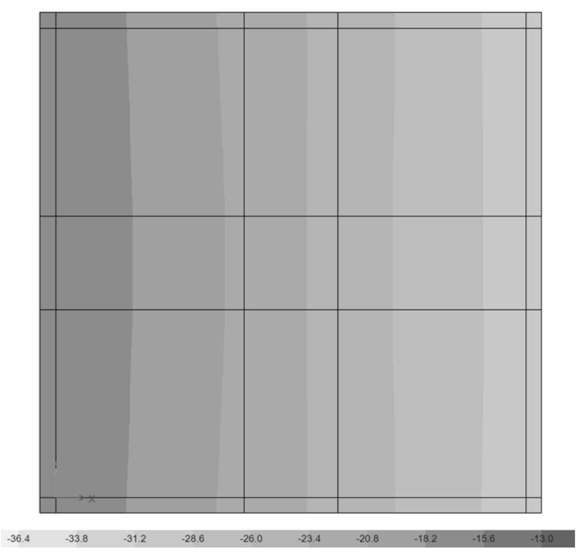

Figure 4: ETABS Deformation Profile

In the case of the deformation profile obtained from ETABS as presented in Figure 4, the deformation profile is much more linearly varying, with a much higher amount of deformation observed below the foundation. The maximum value of the deformation (36.4 mm) is found at the right-side edge of the foundation as the lateral earthquake load is working on the structure from the left to the right side. The minimum amount (13.0 mm) of downward deformation is seen on the left-side edge because, at this edge, the lateral load from the earthquake is trying to overturn the structure with respect to the right-side edge. In the ETABS model, no upward movement of the soil can be perceived below the foundation, which is analogous to the deformation profile found in the PLAXIS 3D model, directly below the boundary of the mat foundation.

3.5 Mat foundation Moment Comparison

While considering the moments along the X-axis, the maximum positive moment is found inside and near the lift core, in both the PLAXIS 3D (Figure 5) and ETABS (Figure 6) models. At the same time, the maximum negative moment is found just outside the lift core in ETABS (soil as area springs), while it is found in the area surrounding the lift core in the case of the PLAXIS 3D model. Nevertheless, significant variations in the values of the moments can be found in the two different models. In the case of PLAXIS 3D model, a maximum positive moment of 650 kN-m/m can be detected, compared to only 150 kN-m/m moment in the ETABS model. At the same time, the opposite situation occurred in the case of negative moments. The maximum negative moment is 500 kN-m/m in the case of the ETABS model, opposed to a maximum of 350 kN-m/m negative moment in the PLAXIS 3D model.

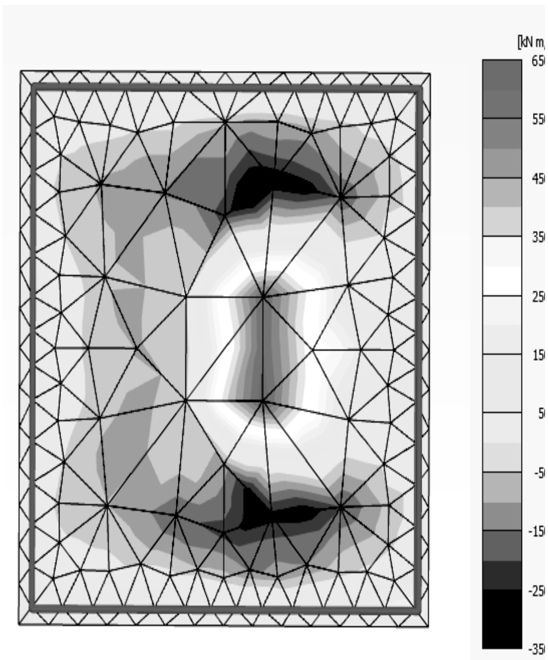

Figure 5: Moment along X-axis (PLAXIS 3D)

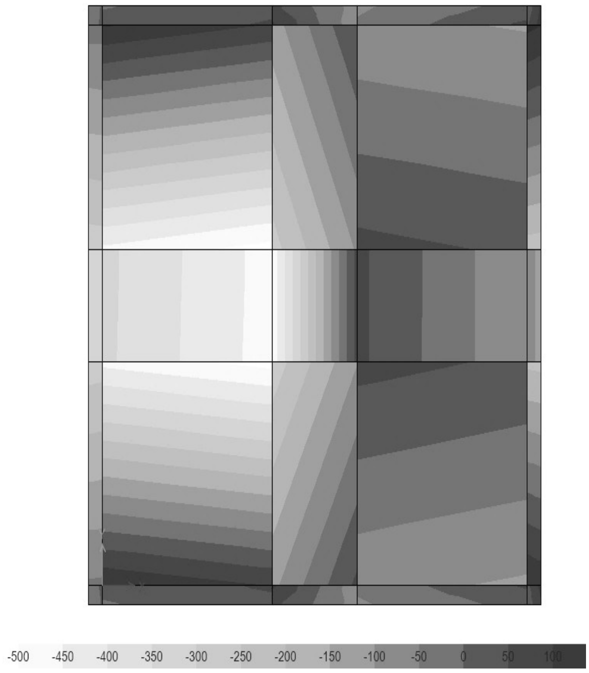

Figure 6: Moment along X-axis (ETABS)

From the analysis of the moments of the mat foundation along the Y-axis, it can be observed that both the maximum positive and negative moments are found surrounding the lift core, in both the PLAXIS 3D and ETABS models. Despite that, significant variations in the values of the moments can still be found in the two different models, comparable to the case of the moment values found along the X-axis. In the case of PLAXIS 3D model, as shown in Figure 7, a maximum positive moment of 1200 kN-m/m can be detected compared to only 600 kN-m/m moment from the ETABS model, shown in Figure 8. Meanwhile, the occurrence of the opposite situation can be noticed in the case of negative moments. While the maximum negative moment is 960 kN-m/m in the case of the ETABS model, only a maximum of 600 kN-m/m negative moment can be ascertained from the PLAXIS 3D model.

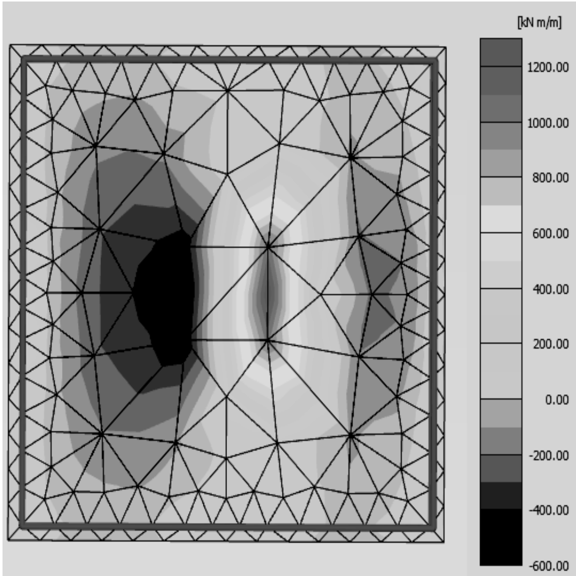

Figure 7: Moment along Y-axis (PLAXIS 3D)

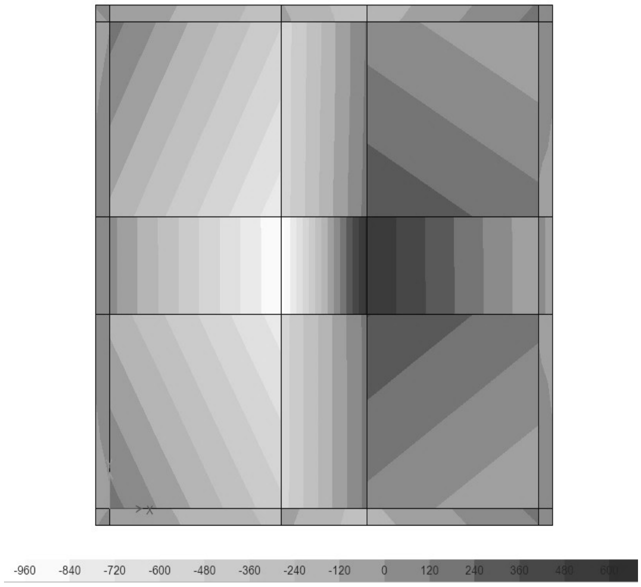

Figure 8: Moment along Y-axis (ETABS)

From the comparison of the moments, it is conspicuous that the consideration of SSI is causing significant modifications in the moment profile of the foundation and even increasing the moment in some instances. This is contrary to the general belief that SSI has positive effects on the structure by lengthening the time-period. This additional moment is mainly coming from the rotational inertia of the total system including the soil profile (Figini & Paolucci, 2016), which is not present in the ETABS model.

To check whether the consideration of soil spring constant along the X-axis and Y-axis changes the moment profile of the soil below the foundation, analysis is performed in ETABS again. The following moment profiles, illustrated in Figure 9 and 10, are found from the ETABS model with 10 percent of the vertical soil spring constant considered for both the X-axis and Y-axis. This consideration is taken into account as this type of analysis is often performed by the practicing engineers in Bangladesh for the design of mat foundations.

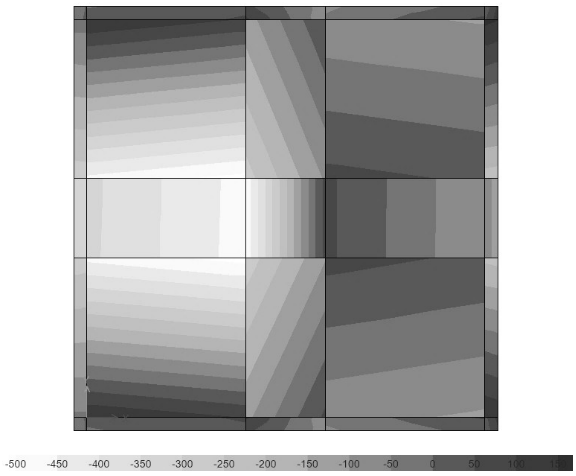

Figure 9: Moment along X-axis (ETABS)

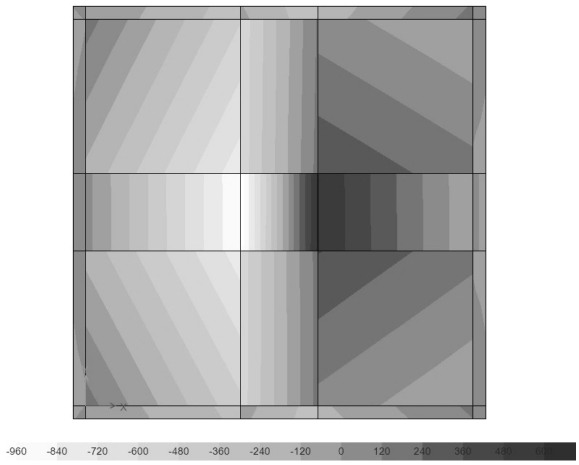

Figure 10: Moment along Y-axis (ETABS)

From the comparison of the Figures 6 and 9, which are virtually identical, it can be stated that the addition of soil spring constant along the horizontal axes has no influence on the moments of the base along the X-axis. This is also found to be the case for the moments in the Y-axis from the comparison of the Figures 8 and 10.

4. CONCLUSION

In the present study, how the consideration of soil-structure interaction can affect the behavior of the structure and analysis of the structure is investigated. From the comparison of the results obtained from ETABS and PLAXIS 3D, it is apparent that the effects of SSI are not just as simple as a lengthening of the fundamental time-period of the structure and a reduction in base shear at the foundation. The obtained outcomes clearly indicate that the consideration of SSI increases the deflection and drift of the structure frame as well as causes a reduction in the moments to which beams are subjected. All those things refer to an increase in the time-period of the structure. However, in the case of the moments at the foundation, an increase is noticed due to rotational inertia. This observation indicates that the common belief about the beneficial effects of SSI may be mistaken. That being the case, it can be said that the implementation of SSI in structural analysis can lead to an overall increase in the safety of the structure.

REFERENCES

Ali, T., Eldin, M. N., & Haider, W. (2023). The Effect of Soil-Structure Interaction on the Seismic Response of Structures Using Machine Learning, Finite Element Modeling and ASCE 7-16 Methods. *Sensors*, Vol. 23. DOI: 10.3390/s23042047

Applied Technology Council. (2020). *A Practical Guide to Soil-Structure Interaction*. Federal Emergency Management Agency, P-2091.

Finini, R. & Paolucci, R. (2016). Integrated foundation-structure seismic assessment through non-linear dynamic analysis. *International Association for Earthquake Engineering*, Vol. 46, 349-367. DOI: 10.1002/eqe.2790

Ganjavi, B., & Hao, H. (2012). Strength reduction factor for MDOF soil-structure systems. *Structural Design of Tall and Special Buildings*, Vol. 23, Issue 3, pp. 161–180. DOI: 10.1002/tal.1022

Housing and Building Research Institute. (2020). *Bangladesh National building Code 2020*.

Liu, S., Li, P., Zhang, W., & Lu, Z. (2020) Experimental study and numerical simulation on dynamic soil-structure interaction under earthquake excitations. *Soil Dynamics and Earthquake Engineering*, Vol. 138. DOI: 10.1016/j.soildyn.2020.106333

Mortezaee, M. & Akhtarpour, A. (2016). Validation of the Structural Analysis by PLAXIS 2D Geotechnical Software. *Geo-China*, 25-32. DOI: 10.1061/9780784480021.004

Mylonakis, G., Nikolaou, S., & Gazetas, G. (2006). Footing under seismic loading: Analysis and design issues with emphasis on bridge foundations. *Soil Dynamics and Earthquake Engineering*, Vol. 26, 824–853. DOI: 10.1016/j.soildyn.2005.12.005

Sharma, N., Dasgupta, K., & Dey, A. (2020). Natural Period of Reinforced Concrete Building Frames on Pile Foundation Considering Seismic Soil-Structure Interaction Effects. *Structures*, Vol. 27, pp. 1594–1612. DOI: 10.1016/j.istruc.2020.07.010

Stewart, J. P., Seed, R. B., & Fenves, G. L. (1999). Seismic soil-structure interaction in buildings. II: Empirical findings. *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 125, 38–48. DOI: 10.1061/(ASCE)1090-0241(1999)125:1(38)

Wani, F. M., Vemuri, J., Rajaram, C., & Babu R, D. V. (2022). Effect of soil structure interaction on the dynamic response of reinforced concrete structures. *Natural Hazards Research*, Vol. 2, Issue 4, pp. 304–315. DOI: 10.1016/j.nhres.2022.11.002

Wolf, J. P., & Obernhuber, P. (1985). Non-linear soil-structure-interaction analysis using dynamic stiffness or flexibility of soil in the time domain. *Earthquake Engineering & Structural Dynamics*, Vol. 13, Issue 2, pp. 195–212. DOI: 10.1002/eqe.4290130205