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Research Article

Effect of soil-foundation interaction on the reinforced concrete multi-storey buildings

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Abstract

Soil-foundation interaction plays an important role in the design of reinforced concrete multi-storey buildings and in the behavior of structures laid on a soil medium. This study investigates the effects of soil-foundation interaction on the reinforced concrete multi-storey buildings of different heights (2, 4, and 6 storey) and supported by three different types of foundations including raft, strip, and isolated foundations. The selected case studies have been analyzed using finite element method implemented by PLAXIS 3D software based on the Mohr-Coulomb soil model. The effect of soil–foundation interaction on the maximum settlement and the internal forces developed in structural elements including axial force, bending moment, and shear force is evaluated. It is found that the maximum settlement reached 118.4 mm in the 6-storey raft foundation case while, the axial force in columns, bending moment in beams, and shear force in beams have varied up to 37.11%, 107%, 57.2%, respectively by considering soil-foundation interaction compared to those in buildings with fixed ends at base.

1. Introduction

Soil-foundation interaction is a critical engineering issue in structural analysis and design, as it directly affects the distribution of internal forces within various structural elements [1,2]. Traditional analysis models often assume that foundations rest on rigid, non-deformable soil. This assumption simplifies the behavior of the structural system but does not accurately reflect reality, particularly in multi-storey buildings that generate significant loads transferred to the soil via the foundations [3-6]. The type of foundation used plays a crucial role in assessing the impact of soil-foundation interaction. In isolated footings, contact with the soil occurs at separate points, while in strip footings, contact extends along the length of the building. In raft foundations, contact with the soil covers the entire building footprint. This results in different values of differential settlement for each foundation type, leading to varying effects on the internal forces of the structural elements. Soil properties, such as modulus of elasticity, cohesion, angle of internal friction, and stress distribution pattern beneath the foundations, play a fundamental role in determining the structural response under static loads [7-10]. Considering soil-foundation interaction in the analysis led to significant variations in the values of axial force, shear force, and bending moment developed in columns and beams [11-14]. This effect is particularly pronounced in multi-storey buildings, where settlement varies between different support points amplifying and altering the load transfer path within the structural system [15-17]. Many researchers have investigated the effect of soil-structure interaction on the reinforced concrete buildings, through several parameters such as displacement, storey drift, moments and forces developed in structural members. Some of the researchers have considered the soil-structure interaction. Among them Ramakant & M. S. Hora [18] studied the effect of soil-structure interaction on 2-bay 2-storey reinforced concrete building

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using finite element method. They evaluated the effect of differential settlement on shear force and bending moment developed in structural elements. Their results showed that the differential settlement has a significant effect on the values of shear forces and bending moment in structural members. Jancy F. et al. [19] studied the effect of soil-structure interaction on RC multi-storey buildings using finite element method with ANSYS software. They found that the soil-structure interaction has a significant effect on frame behavior and should be considered in the structural analysis of sensitive buildings. Garg et al. [20] investigated the interaction behavior of 3-bay 3-storey reinforced concrete frame supported by footing with strap beam and resting on soil mass using finite element method. They found that the soil-structure interaction has a significant effect on redistribution of end moments in structures. Raksha J. Khare et al. [21] studied the effect of soil-structure interaction on a 2-bay 4-storey frame structure supported by pile foundation embedded in cohesive soil. Their results showed that displacements in the fixed base condition were lower than when soil-structure interaction was considered. Chore et al. [22] studied the effect of interaction analysis on framed structure supported by pile foundations embedded in a soil system using finite element method. They found that the soil-structure interaction increased the top displacement and had little effect on the maximum absolute moment in the columns. Santos & Correa [23] evaluated the load redistribution generated due to soil-structure interaction in a concrete wall building through iterative numerical analysis. Their results showed an inclination for load transfer from supports under larger settlements to supports with fewer settlements. Bezih et al. [24] implemented a finite element model to evaluate the influence of soil-structure interaction on reinforced concrete structures, considering long-term soil changes. Numerical simulations were performed on different soft soil types, highlighting the importance of soil compressibility and its anisotropy in assessing the safety of reinforced concrete structures. Ayat Errah Remadna et al. [25] studied the effect of soil-structure interaction on reinforced concrete buildings resting on homogeneous and heterogenous soils using finite element method. They found that the soil-structure interaction should be considered especially in highly compressible soils. Several studies have investigated the effect of soil–structure interaction using numerical methods such as the finite element method. PLAXIS 3D has been widely adopted for modelling soil-structure interaction, demonstrating that soil flexibility significantly affects internal force distribution and settlement behavior in structural systems [26,27]. The summary of the literature review is given in Table 1.

Table 1. Summary of previous soil-structure interaction studies

Author/Year	Building type	Foundation type	Soil model	Software used	Key finding
Ramakant & Hora [18]	2-bay 2-storey RC	Shallow	Nonlinear soil	FEM	Settlement affects structural forces
Jancy F. et al. [19]	RC multi-storey	Shallow	Nonlinear soil	FEM-ANSYS	Soil nonlinearity influences SSI
Garg et al. [20]	3-bay 3-storey RC	strap Footing	Nonlinear soil	FEM	Forces increase due to SSI
Khare et al. [21]	2-bay 4-storey RC	Pile foundation	Soil-pile interaction	FEM	SSI changes building response
Chore et al. [22]	Framed RC structure	Pile foundation	Nonlinear soil	FEM	Force redistribution due to SSI
Santos & Correa [23]	Wall RC building	Shallow	Elastic-plastic soil	Numerical analysis	SSI affects settlement
Bezih et al. [24]	RC structures	Shallow	Time-dependent	FEM-PLAXIS	Increases structural demand
Remadna et al. [25]	RC structures	Shallow	Time-dependent	FEM	Time effects influence SSI

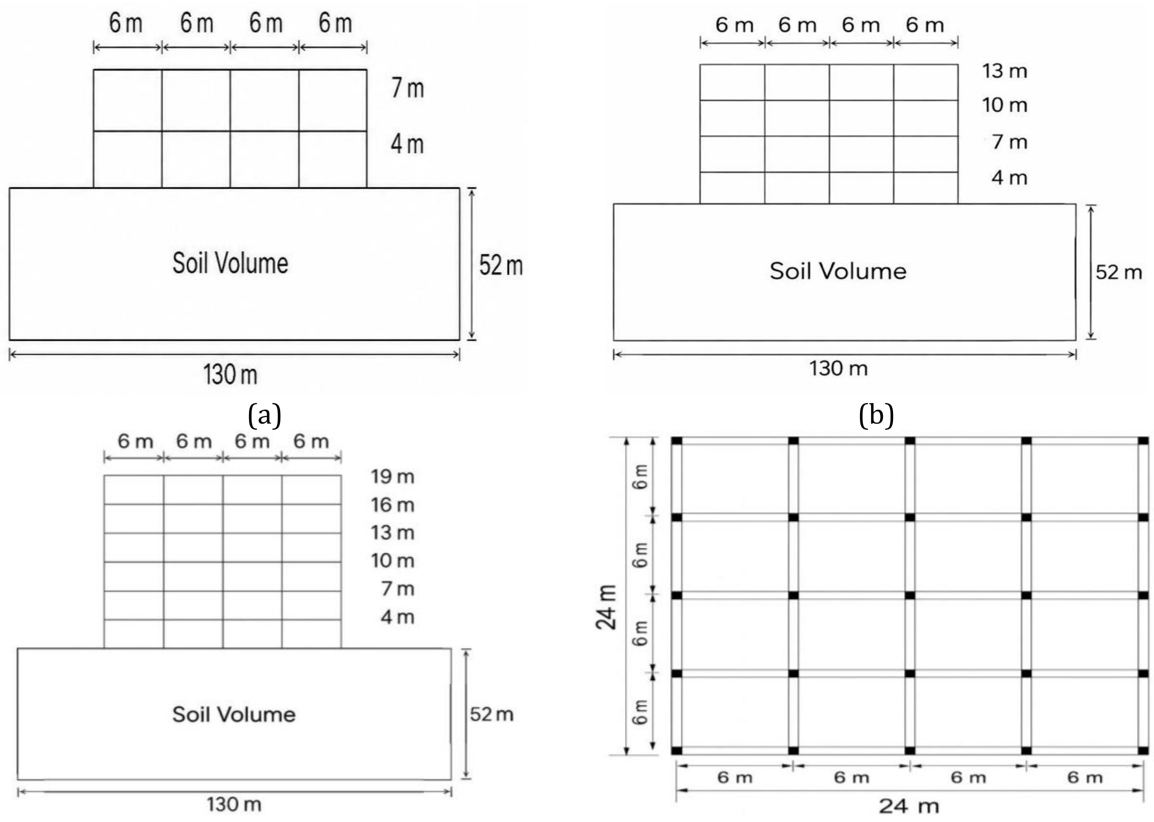
Based on Table 1 most of these studies have focused on simplified structural configurations or single foundation types without a comprehensive comparison between different foundation systems under identical soil conditions.

The study area is located in the middle zone of Basra city, where the subsurface soil characteristics differ from those in the surrounding areas of the governorate. Unlike the outlying areas of Basra, which may contain more varied sandy deposits, the middle zone is characterized mostly by layers of fine to very fine silty clay, with shallow groundwater levels and low bearing capacity, which significantly affects foundation performance and settlement behavior [28]. Geotechnical investigations in Basra have confirmed that the subsoil consists of alternating layers of clay, silty clay, and silty sand. These layers are characterized by high compressibility and relatively low shear strength in the upper layers [28]. These conditions make the area highly sensitive to the effects of soil-structure interaction, particularly for RC multi-storey buildings constructed on shallow foundations.

The aim of this study is to investigate the influence of soil-foundation interaction on building behavior considering soil conditions at the selected site in Basra city. The studied behavior of the buildings involves the variation in the axial force, bending moment, and shear force in structural members compared with fixed base conditions. The effect of soil-foundation interaction on buildings of different heights supported by different types of foundations using the soil properties of the middle zone of Basra city is evaluated using finite element method performed by PLAXIS 3D (version 24). The resulting forces and bending moments in the structural frames have been computed and compared for the two cases with and without soil-foundation interaction. The novelty of this study lies in the comparative analysis of three foundation systems (isolated, strip, and raft) applied to different building heights under the same soil conditions using finite element method implemented in PLAXIS 3D software.

2. Building Model

In the present study, a 4-bay symmetrical reinforced concrete building with different heights (2-storey, 4-storey, and 6-storey) resting on the selected site soil in Basra city is analyzed under the action of dead loads, live loads, and self-weight of the building. The building elevations with different heights and the common plan are shown in Fig. 1.



(a) (b)

(c) (d)

Fig. 1. (a) elevation of 2-storey building (b) elevation of 4-storey building (c) elevation of 6-storey building (d) plan showing slab beam

The building is supported by different types of foundations namely raft foundation, strip footing, and isolated footing depending on building heights and soil bearing capacity. Due to load-bearing capacity limitations, all types of foundations were considered for the 2-storey building, for the 4-storey building strip and raft foundations were adopted, while for the 6-storey building only raft foundation was used. For 6-storey building, isolated and strip footings became less feasible due to higher applied loads and settlement limitations associated with shallow foundations. A four-bay configuration was used in all models, which is commonly used in residential and mid-rise buildings. This configuration ensures uniform stiffness distribution and realistic load transfer mechanisms while maintaining computational efficiency in three-dimensional finite element analysis. The geometric and material properties of proposed frames and foundations are given in Table 2.

Table 2. Geometric and material properties of frames and foundations.

Component	Description	Data
Frame	First storey height	4 m
	Another storey height	3 m
	No. of bays in x and y directions	4
	Bay width in x and y directions	6 m
	Slab thickness	0.2 m
	$f'c$ for beams, slabs, and foundations	30 MPa
	Ec for beams, slabs, and foundations	25742960 kN/m^2
	$f'c$ for columns	40 MPa
	Ec for columns	29725410 kN/m^2
	Concrete Poisson's ratio vc	0.15
	Concrete density γ_c	25 kN/m^3
	Beam dimensions (m)	0.3X0.5
	Column (2 and 4 storey buildings) (m)	0.3X0.3
	Column (6 storey buildings) (m)	0.4X0.4
Raft foundations	Raft plan dimensions (2, 4, and 6 storey buildings) (m)	26X26
Strip footings dimensions	Footing width (2-storey buildings) (m)	1.2
	Footing width (4-storey buildings) (m)	2.4
Isolated footings dimensions	Footing dimensions (2-storey buildings) (m)	Corner: 2X2 Edge: 2.8X2.8 Interior: 3.8X3.8
Foundation's thickness	2-storey (m)	0.6
	4-storey (m)	0.8
	6-storey (m)	1

In the present study, the applied structural loads considered in the numerical model included live load equal to $3kN/m^2$, equivalent wall load equal to $2kN/m^2$ distributed on floor area, and imposed dead load equal to 1.375 kN/m^2 distributed on roof area also, PLAXIS 3D automatically calculated the self-weight of all members. A factored load combination of (1.2DL + 1.6LL) was adopted in accordance with the ACI Committee 318. Building Code Requirements for Structural Concrete (ACI 318-22) [29]. All structural loads were applied as gravity loads, wind and seismic loads were not considered in this study because the main objective is to investigate soil–foundation interaction effects under static loading.

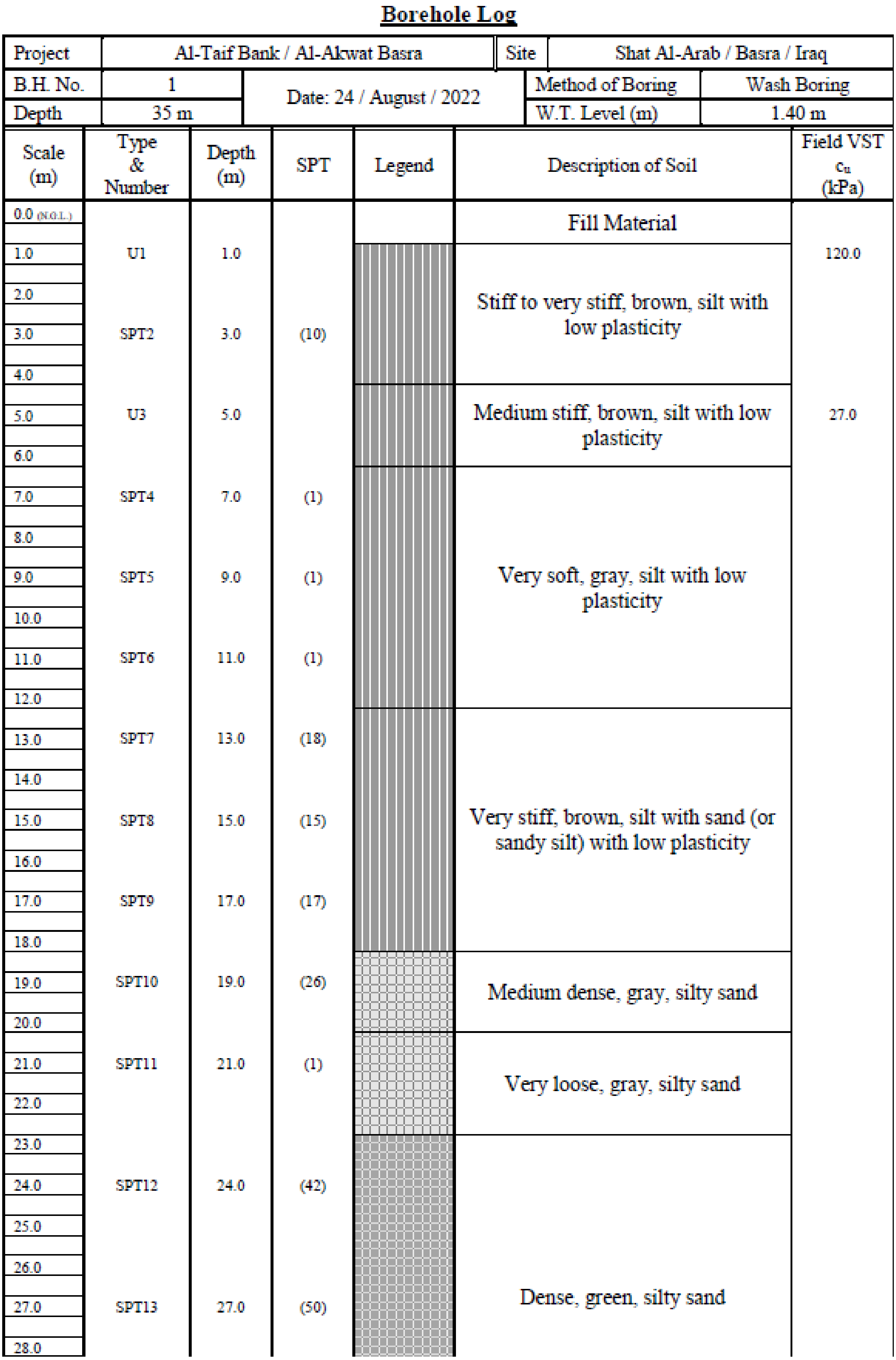
3. Soil Properties

The study site is located in Shat Al-Arab district-Basra Governorate, southern Iraq. Basra soil is characterized as fine to medium-fine alluvial soil, often consisting of clay and silt layers with sandy intrusions depending on location and depth. The geotechnical properties used in this study were obtained from soil Investigation report No. (5/SI/2022), which was conducted by Consulting Bureau-College of Engineering-University of Basrah [30]. The soil profile and properties of this site are given in Table 3.

Table 3. Profile and properties of the soil at Al-Akwat, Shat Al-Arab, Basra [30].

Site	Layer	Description	Data
Al-Akwat, Shat Al-Arab, Basra W.T. Level= 1.4 m	First layer (stiff to medium stiff silt)	Depth range	0-6 m
		Drainage type	Undrained
		Undrained cohesion c	$30\ kN/m^2$
		Friction angle φ	0
		Young's modulus E	$25 * 10^3\ kN/m^2$
		Dry density γ_{dry}	$16\ kN/m^3$
		Saturated density γ_{sat}	$20\ kN/m^3$
		Dilatancy angle ψ	0
		Poisson's ratio v	0.3
		Earth pressure coefficient K_0	1
	Second layer (very soft silt)	Depth range	6-12 m
		Drainage type	Undrained
		Undrained cohesion c	$12\ kN/m^2$
		Friction angle φ	0
		Young's modulus E	$10 * 10^3\ kN/m^2$
		Dry density γ_{dry}	$16\ kN/m^3$
		Saturated density γ_{sat}	$20\ kN/m^3$
		Dilatancy angle ψ	0
		Poisson's ratio v	0.35
		Earth pressure coefficient K_0	1
	Third layer (very stiff silt)	Depth range	12-18 m
		Drainage type	Undrained
		Undrained cohesion c	$50\ kN/m^2$
		Friction angle φ	0
		Young's modulus E	$40 * 10^3\ kN/m^2$
		Dry density γ_{dry}	$16\ kN/m^3$
		Saturated density γ_{sat}	$20\ kN/m^3$
		Dilatancy angle ψ	0
		Poisson's ratio v	0.3
		Earth pressure coefficient K_0	1
	Fourth layer (medium to dense silty sand)	Depth range	>18 m
		Drainage type	Drained
		Cohesion c	$1\ kN/m^2$
		Friction angle φ	36°
		Young's modulus E	$60 * 10^3\ kN/m^2$
		Dry density γ_{dry}	$16\ kN/m^3$
		Saturated density γ_{sat}	$20\ kN/m^3$
		Dilatancy angle ψ	6°
		Poisson's ratio v	0.3
		Earth pressure coefficient K_0	0.41

According to the geotechnical investigation report No. (5/SI/2022), the soil profile consists of four distinct soil layers, including stiff to medium stiff silt, very soft silt, very stiff silt, and medium to dense silty sand. A borehole log illustrating the soil stratification is presented in Fig. 2. The groundwater table was detected at a depth of 1.4 m below the natural ground level and was considered in the analysis to represent in-situ stress conditions. The borehole log presented in Fig. 2 shows several soil layers. For numerical modelling, soil layers with similar engineering properties were grouped into four layers to simplify the finite element model without significantly affecting the overall soil behavior. Also, the shallow fill layer showed near the ground surface was excluded from the analysis because the study focuses on the behavior of the natural bearing strata.



Borehole Log

Project	Al-Taif Bank / Al-Akwat Basra	Site	Shat Al-Arab / Basra / Iraq
B.H. No.	1	Method of Boring	Wash Boring
Depth	35 m	W.T. Level (m)	1.40 m
Date: 24 / August / 2022			

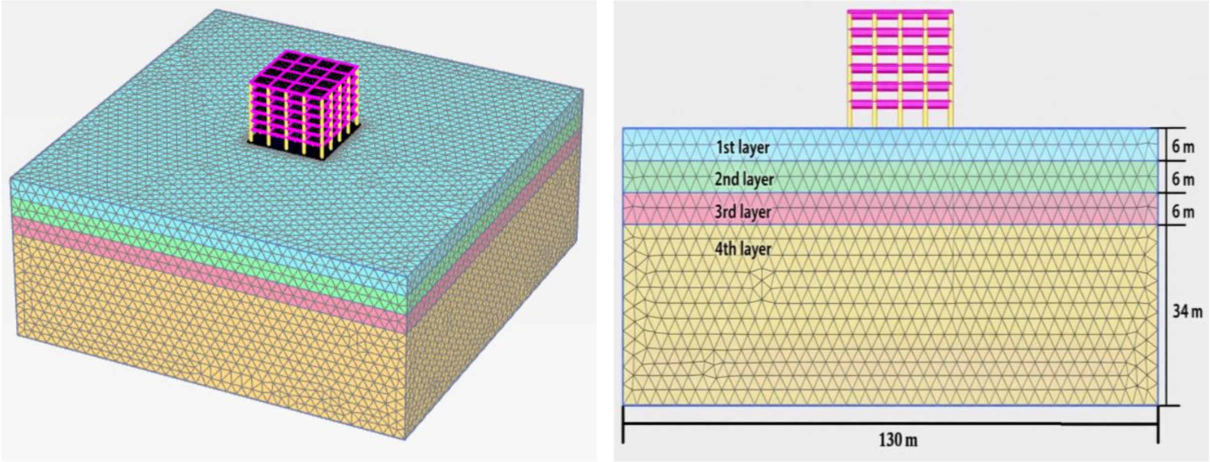
Scale (m)	Type & Number	Depth (m)	SPT	Legend	Description of Soil	Field VST c_u (kPa)
0.0 (N.G.L.)					Fill Material	
1.0	U1	1.0		▥	Stiff to very stiff, brown, silt with low plasticity	120.0
2.0						
3.0	SPT2	3.0	(10)			
4.0						
5.0	U3	5.0		▥	Medium stiff, brown, silt with low plasticity	27.0
6.0						
7.0	SPT4	7.0	(1)	▥	Very soft, gray, silt with low plasticity	
8.0						
9.0	SPT5	9.0	(1)			
10.0						
11.0	SPT6	11.0	(1)			
12.0						
13.0	SPT7	13.0	(18)	▥	Very stiff, brown, silt with sand (or sandy silt) with low plasticity	
14.0						
15.0	SPT8	15.0	(15)			
16.0						
17.0	SPT9	17.0	(17)			
18.0						
19.0	SPT10	19.0	(26)	▦	Medium dense, gray, silty sand	
20.0						
21.0	SPT11	21.0	(1)	▦	Very loose, gray, silty sand	
22.0						
23.0				▦	Dense, green, silty sand	
24.0	SPT12	24.0	(42)			
25.0						
26.0						
27.0	SPT13	27.0	(50)			
28.0						

Fig. 2. Borehole log of the study site [30]

The unit weight values were obtained from the soil investigation report and slightly rounded for numerical modeling purposes. Representative values were adopted for all soil layers due to the minor variation between them. The Mohr-Coulomb model is used in this study because it requires five primary soil parameters (cohesion, friction angle, Young's modulus, Poisson's ratio, and Dilatancy angle), all of which are available from the site investigation report.

4. Finite Element Modeling

The complex interaction between the foundations and its surrounding soil is carried out using PLAXIS 3D software (version 24). The soil–foundation–structure interaction system was modeled in three dimensions to realistically capture the stress redistribution and deformation behavior of the soil and structural components. The finite element simulation of frame-foundation-soil system is shown in Fig. 3. The soil extent was defined with overall dimensions of 130 m X 130 m in plan and 52 m in depth. The adopted domain size corresponds to approximately five times the raft foundation width (5B), where an extension of about two times the foundation width (2B) was provided in each horizontal direction beyond the building. The PLAXIS 3D software automatically sets the default boundary conditions. The bottom boundary is completely fixed in all directions, while the vertical boundary is restricted in the normal direction (normally fixed) and free in the tangential directions. The top boundary is free, allowing for deformation under applied loads.



(a) (b)

Fig. 3. Finite element simulation of frame-foundation-soil system in the: (a) 3D view, and (b) side view

Table 4. Element types and degrees of freedom in PLAXIS 3D model

Element	Type in PLAXIS 3D	Degree of freedom (DOF)
Soil	10-node tetrahedral element	Three DOF
Beams and columns	3-node beam element	Six DOF
Foundations and slabs	6-node triangular element	Five DOF
Interface	12-node triangular element	Three translational DOF

The soil medium is represented using 10-node tetrahedral elements and its mechanical behavior modeled using Mohr-Coulomb criterion in PLAXIS 3D. The frame members (beams and columns) are represented using 3-node beam element with six degrees of freedom. The foundations and slabs are represented using 6-node triangular element with only five degrees of freedom. The interface between the foundation and its surrounding soil is modeled using 12-node triangular elements with three translational degrees of freedom. This element allows for slip or relative separation (slip/gap) and is the essential element for realistically representing soil-foundation interaction. The interface strength reduction factor (Rinter) was taken as 1.0, assuming full contact between the foundation and the soil. This assumption is considered reasonable for cohesive soils under undrained conditions, where separation at the interface is limited. In numerical analysis using

PLAXIS 3D, the initial phase was used to generate the initial soil stresses, and then in the next phase the structural model was fully activated with applied loads to analyze soil-foundation interaction. The finite element types used in the PLAXIS 3D model with their degrees of freedom are summarized in Table 4.

4.1. Mesh Sensitivity Analysis

A mesh sensitivity analysis was performed to ensure the independence of numerical results from mesh refinement. A four-storey building supported by a raft foundation was chosen as a representative case because it represents an intermediate structural configuration. Three different mesh densities, coarse, medium, and fine were evaluated. The maximum settlement below the raft foundation was selected as the primary comparison criterion. The number of elements, number of nodes, and settlement values for each mesh configuration are presented in Table 5.

Table 5. Mesh sensitivity analysis results for the four-storey building supported by raft foundation

Mesh type	Number of elements	Number of nodes	Maximum settlement (mm)	Variation (%)
Coarse	4581	11840	62	-
Medium	9582	22272	63	1.61
Fine	21018	43482	64	1.56

Based on Table 5, the results show that the maximum settlement increased from 62 mm for the coarse mesh to 63 mm for the medium mesh and 64 mm for the fine mesh. The percentage variation between the medium and fine mesh was only 1.56%, which is well below the commonly accepted threshold of 5%, confirming mesh independence of the numerical results. All analyses in this study were performed using a fine mesh configuration, where this mesh density was maintained throughout the study to ensure maximum numerical accuracy.

4.2. Model Validation

To verify the reliability of the finite element model, a validation procedure was conducted by comparing the numerical results obtained from PLAXIS 3D with experimental data reported from a previously published plate load test study. Safa Cevik (2022) [31] investigated the settlements of construction site in Ankara/Türkiye using plate load test. The plate width is 450mm, and the thickness is 25mm. The loads increased by 6 stages as 50, 130, 220, 330, 450, 550 kPa, and the settlement was recorded at each stage, and load-settlement curves were plotted. The researcher also numerically modeled the test using PLAXIS 2D software, relying on axial symmetry and the Mohr-Coulomb model. Elasticity theory was employed to perform analytical solutions and calculate soil parameters such as the elastic modulus and the coefficient of reaction. The field results were then compared with the analytical and numerical results, this research demonstrated good agreement between them. This provided a suitable basis for remodeling using PLAXIS 3D software and validating the published experimental results. The subgrade material soil properties are (E=149 MPa, c=10 kPa, and $\emptyset$=42°). The comparison between the numerical and experimental load–settlement results is presented in Fig. 4.

By comparing the results of numerical modeling using PLAXIS 3D software with the practical results of the selected study. It is evident that the results determined from PLAXIS 3D are in good agreement with results obtained from experimental test, which confirms the accuracy of the numerical model used and its ability to represent the real behavior of the soil and the structural elements interacting with it. It was concluded that PLAXIS 3D with foundations and nonlinear soil behavior models resulted in very good behavior. In addition, the model behavior is assessed by comparison with the trends reported in previous experimental and numerical studies on soil-structure interaction [32], [33], which highlight the effect of soil elasticity on settlement behavior and structural response.

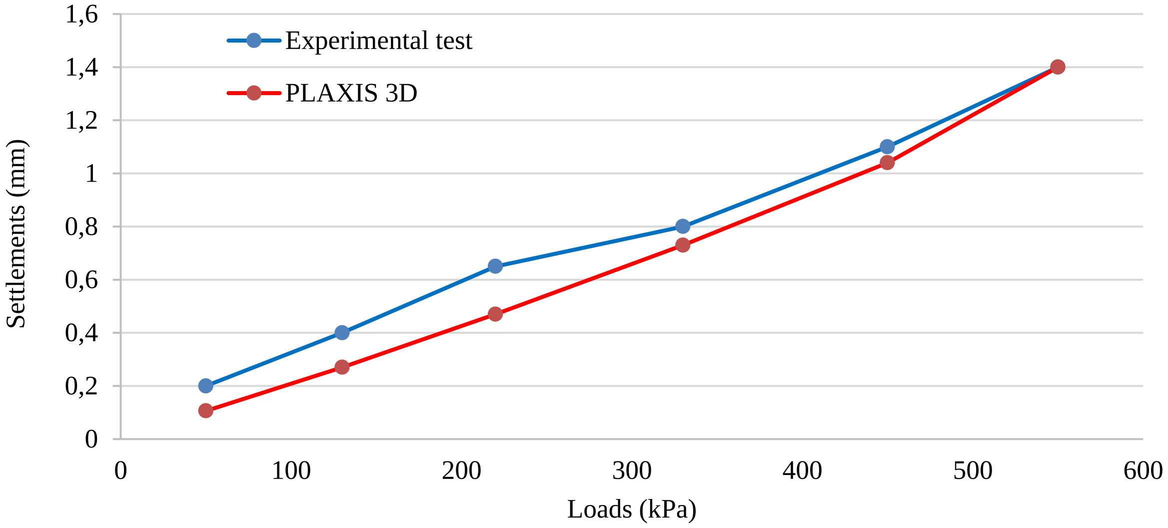


Fig. 4. Comparison between the numerical and experimental load–settlement results

5. Results and Discussions

In this study, the results of maximum and differential settlement, along with variations in axial force, bending moment, and shear force, are presented in the following subsections.

5.1. Settlement Analysis

The maximum settlement results of the studied models under different foundation types and specified building heights are presented using Figs. 5–8, which display the settlement distribution and the deformed mesh obtained from PLAXIS 3D analysis. In addition, Table 6 summarizes the maximum and differential settlement values for each analytical case to facilitate comparison between different models.

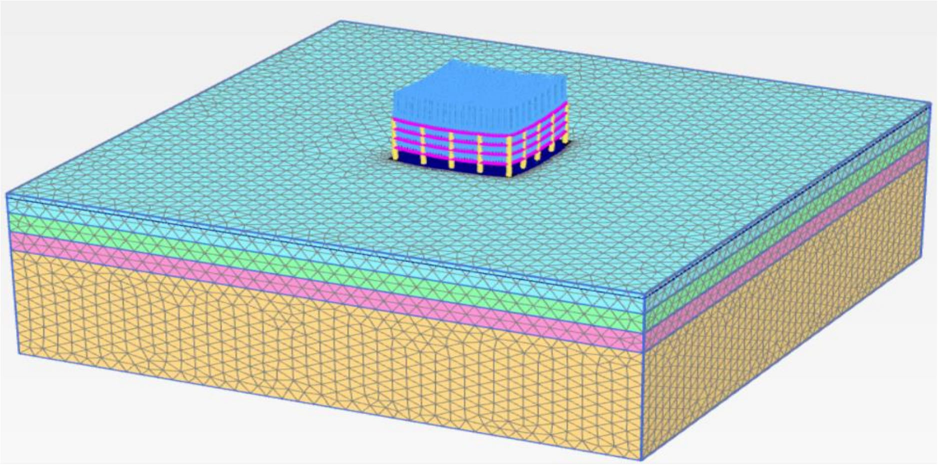


Fig. 5. Deformed mesh of the 4-storey building with raft foundation

Figs. 5–8 illustrate the settlement distribution and deformation of the studied models, while Table 6 shows the maximum and differential settlement values for each case. For the 2-storey building, the strip footing recorded the lowest maximum settlement of 26.41 mm and differential settlement of 19.75 mm, while the raft foundation recorded the highest maximum settlement of 33.78 mm. As the building height increased to 4-storeys, the maximum settlement increased to 60.73 mm for the strip footing and 64.54 mm for the raft foundation, while the differential settlement increased to 49.12 mm and 46.45 mm, respectively. In the case of the 6-storey building, the raft recorded the highest maximum settlement of 118.4 mm and differential settlement of 45.77 mm due to the increased applied loads. Overall, the results showed a gradual increase in settlement with the increase in the number of storeys and the loads transferred to the soil. The difference in settlement values between different foundations may cause a redistribution of loads within structural members due to changes in support conditions, which will be explained in the forces and moment results.

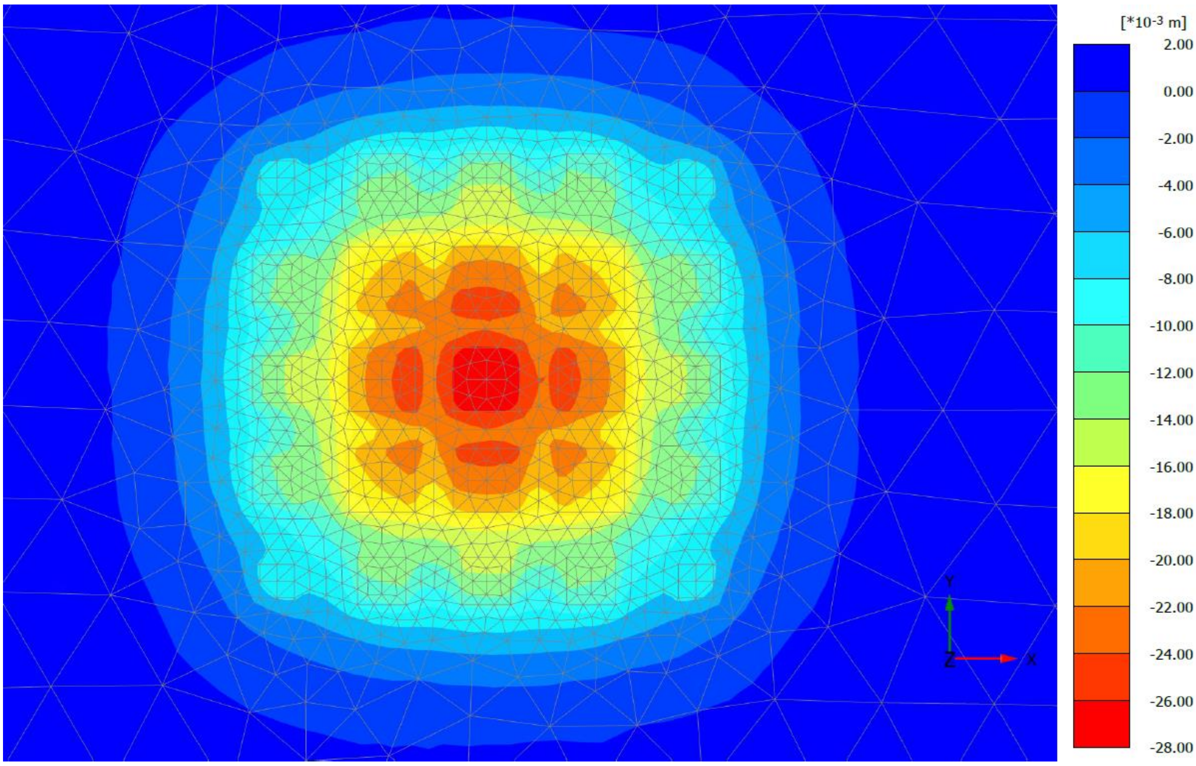


Fig. 6. Settlement distribution for 2-storey building with isolated footing

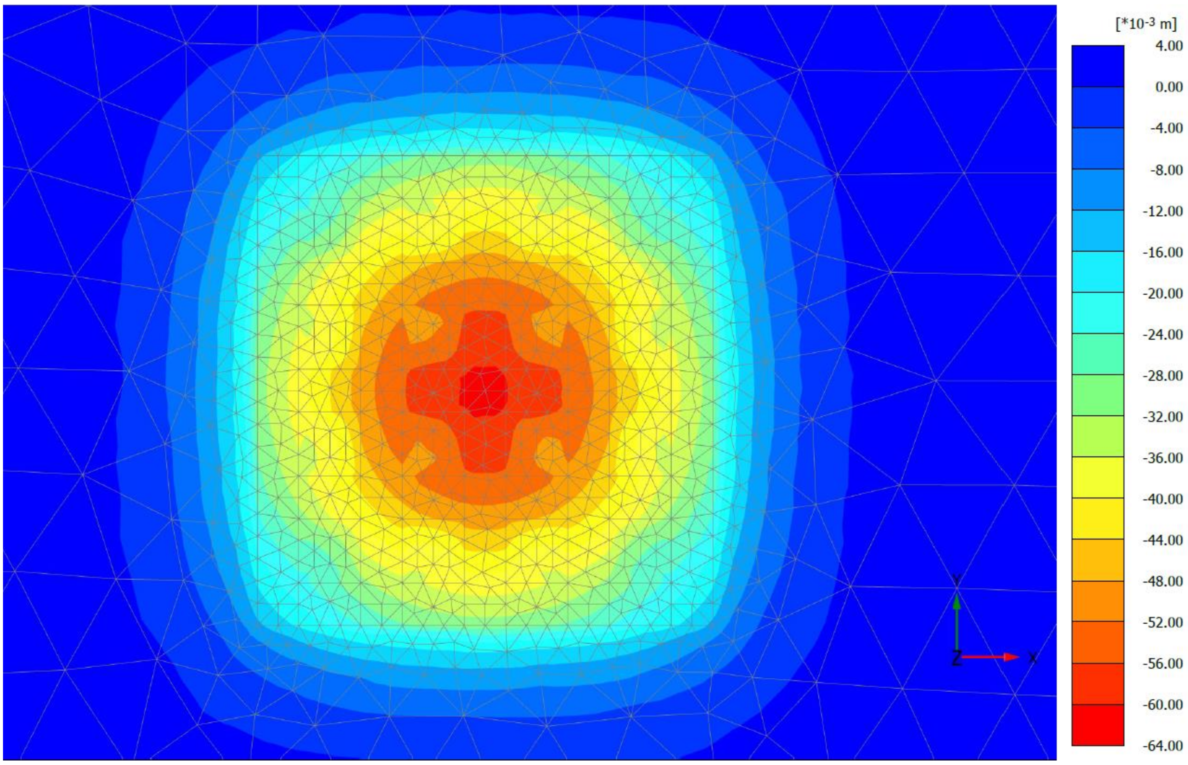


Fig. 7. Settlement distribution for 4-storey building with strip footing

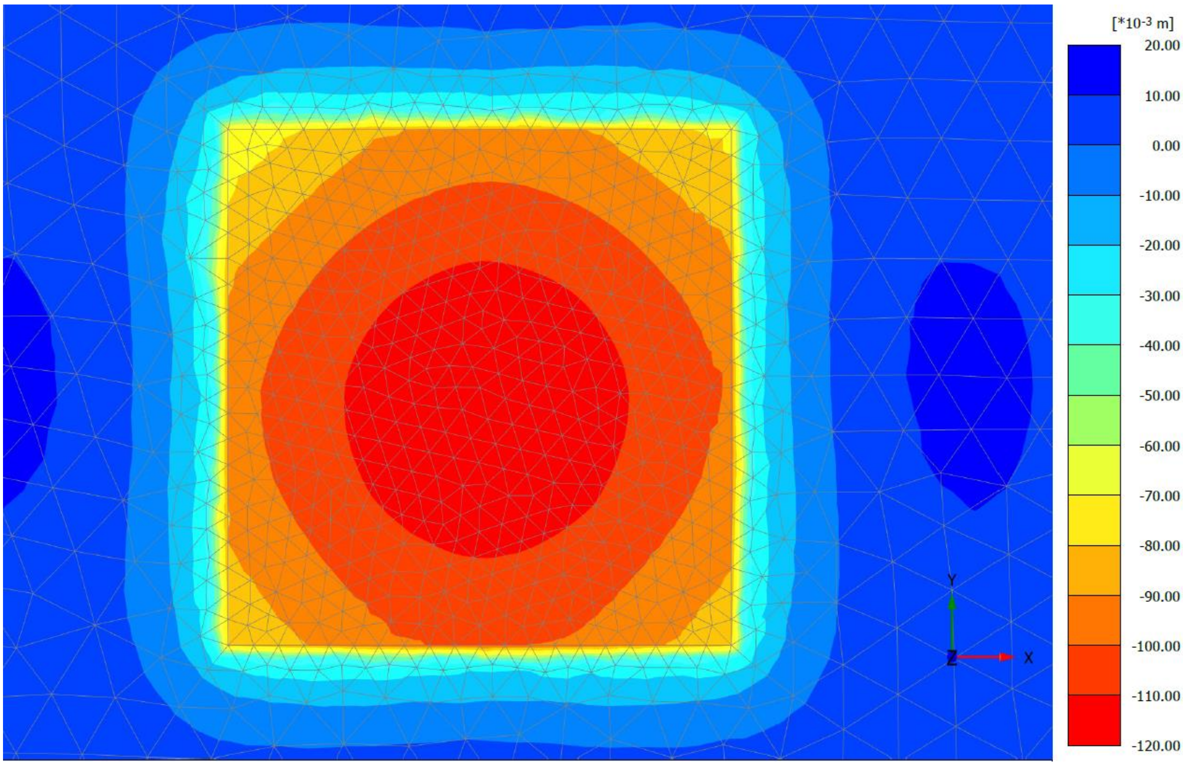


Fig. 8. Settlement distribution for 6-storey building with raft foundation

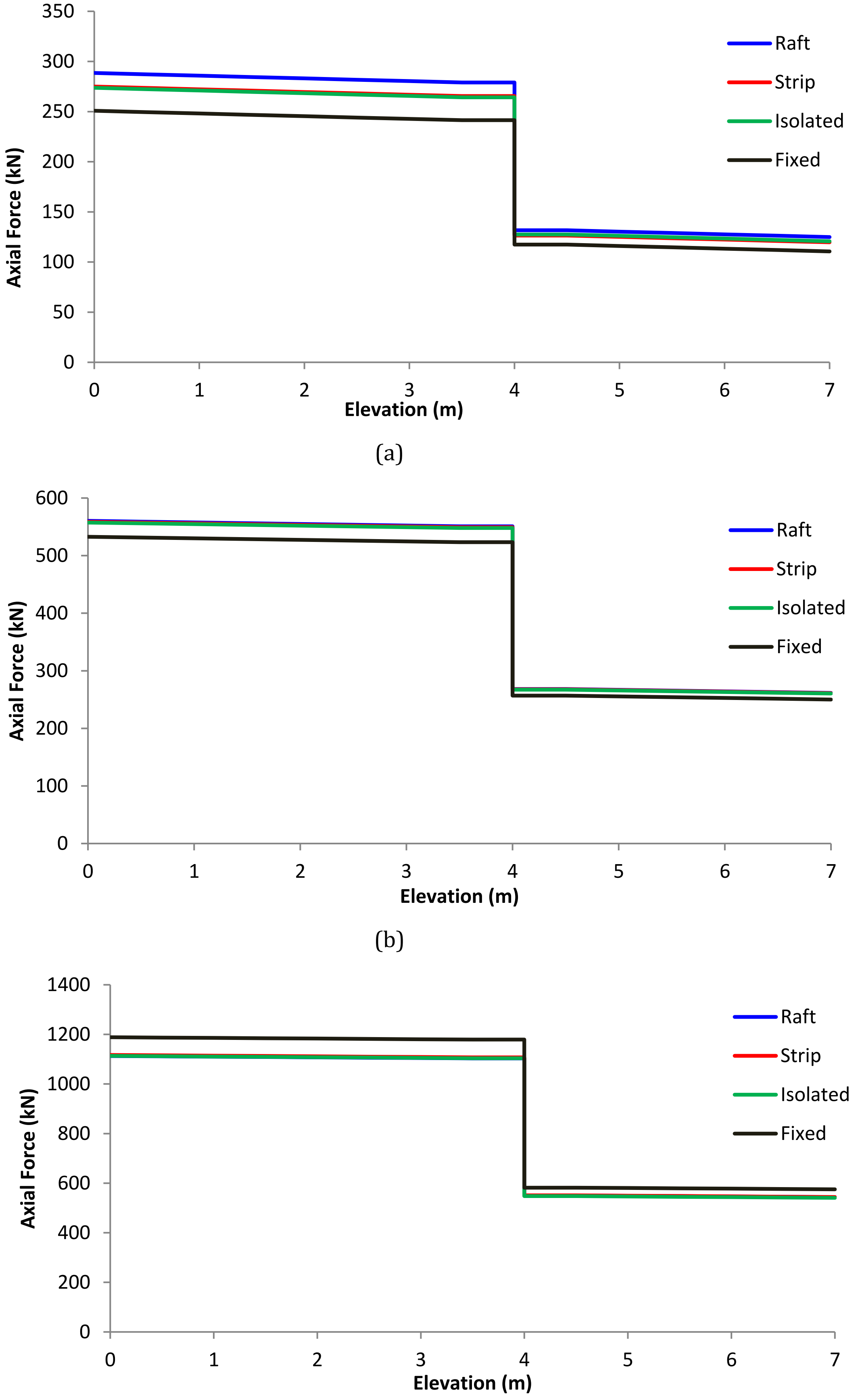
Table 6. Maximum and differential settlement values for different building heights and foundation types

No. of storey	Foundation type	Maximum settlement (mm)	Differential settlement (mm)
2-storey	Isolated footing	26.96	21.13
	Strip footing	26.41	19.75
	Raft foundation	33.78	27.19
4-storey	Strip footing	60.73	49.12
	Raft foundation	64.54	46.45
6-storey	Raft foundation	118.4	45.77

5.2. Axial Force

The axial forces developed in columns are among the most important indicators of soil-foundation interaction, as their values are significantly affected by soil properties, stiffness, and the type of foundation. The variations of axial force in the columns for the building are presented in Figs. 9-11 and summarized in Table 7. It is obvious that considering the soil-foundation interaction leads to variations in the distribution of vertical loads between columns.

Table 7 and Figs. 9-11 illustrate the variation in axial column forces under fixed and flexible foundation conditions for different building heights. For the 2-storey building, soil-foundation interaction (SFI) resulted in an increase in the axial force of the corner columns by approximately 8.6%, 9.6%, and 15% for isolated, strip, and raft foundations, respectively, while the edge columns experienced increases ranging from 4.6% to 5.2%. Conversely, the axial forces of the interior columns decreased by approximately 6%, indicating a redistribution of loads from the interior columns to the perimeter columns. For the 4-storey building, the effect of SFI became more pronounced, with the forces of the corner columns increasing by 28.8% and 32% for strip and raft foundations, respectively, while the forces of the edge columns increased by 6.9% to 8.6%. Meanwhile, the forces of the interior columns decreased by approximately 8.5% to 9.9%.

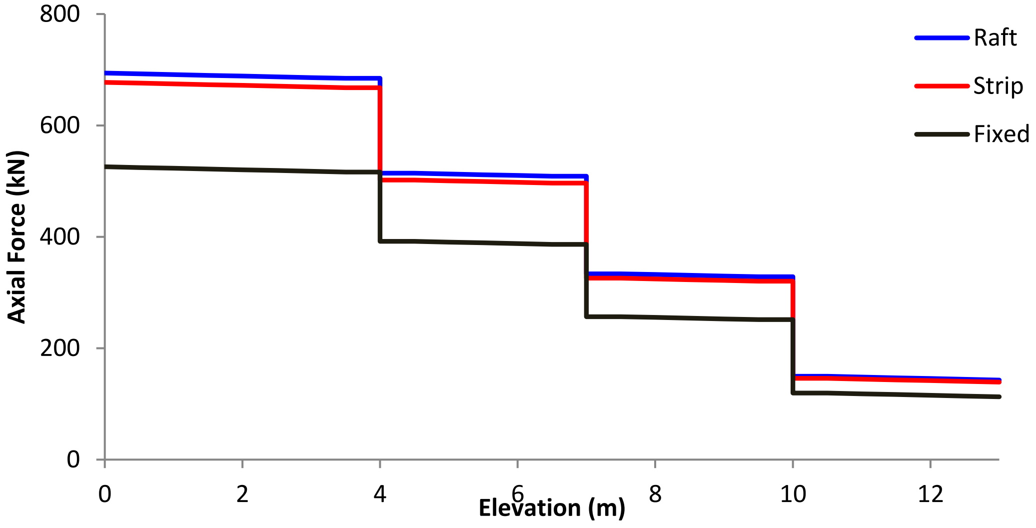


(a)

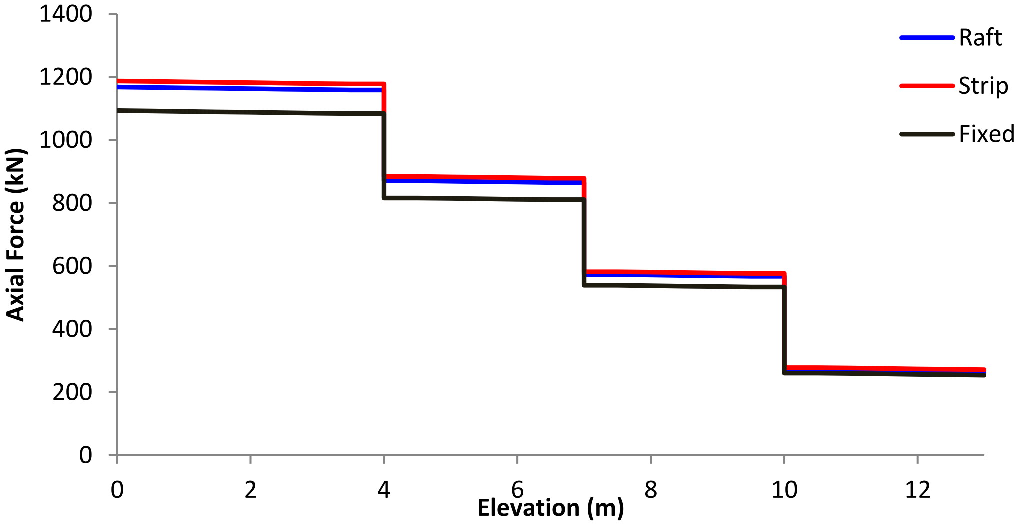
(b)

(c)

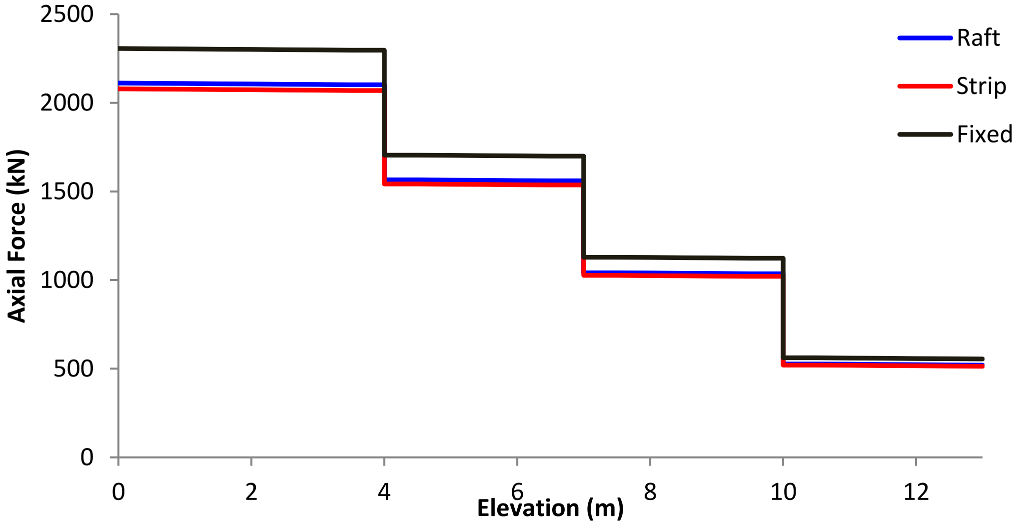
Fig. 9. Column axial force for 2-storey building: (a) corner column, (b) edge column, (c) interior column



(a)

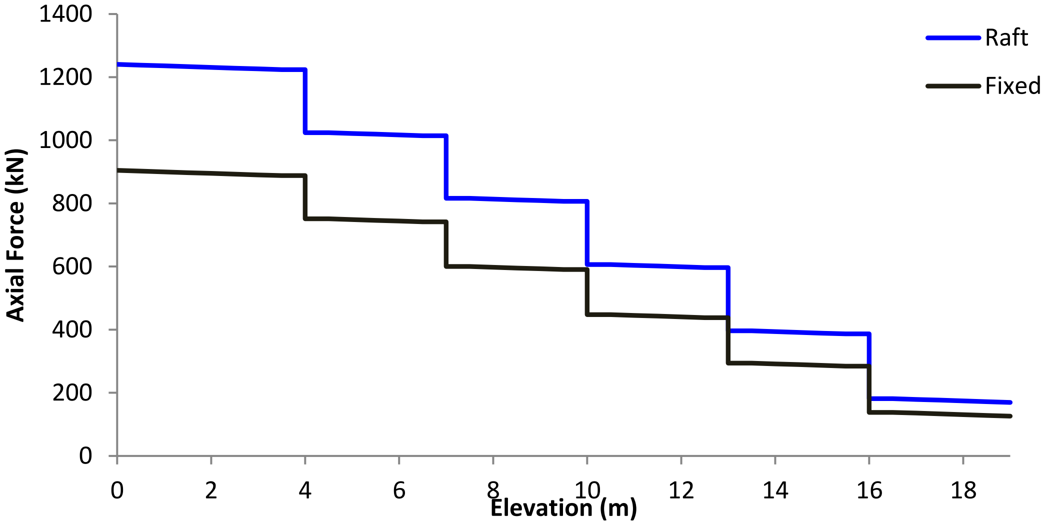


(b)

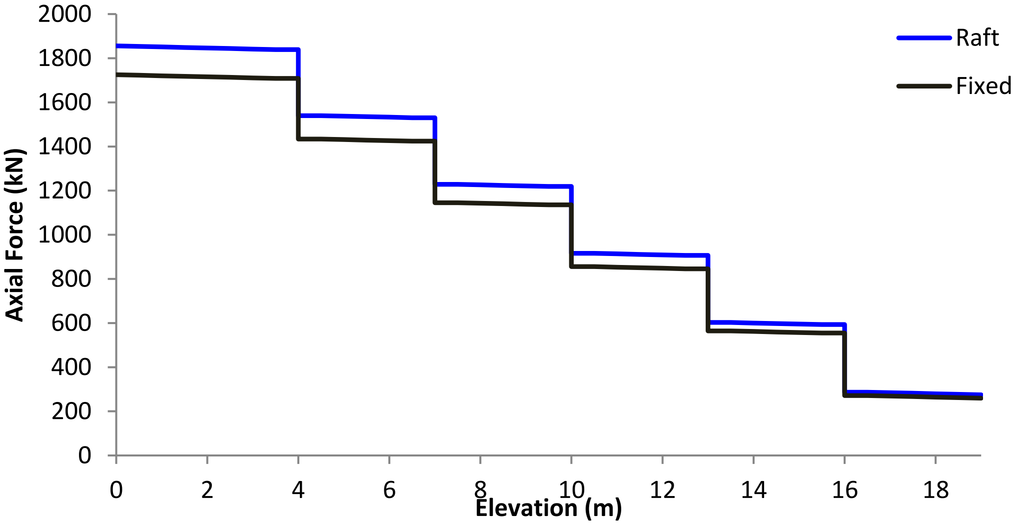


(c)

Fig. 10. Column axial force for 4-storey building: (a) corner column, (b) edge column, (c) interior column



(a)



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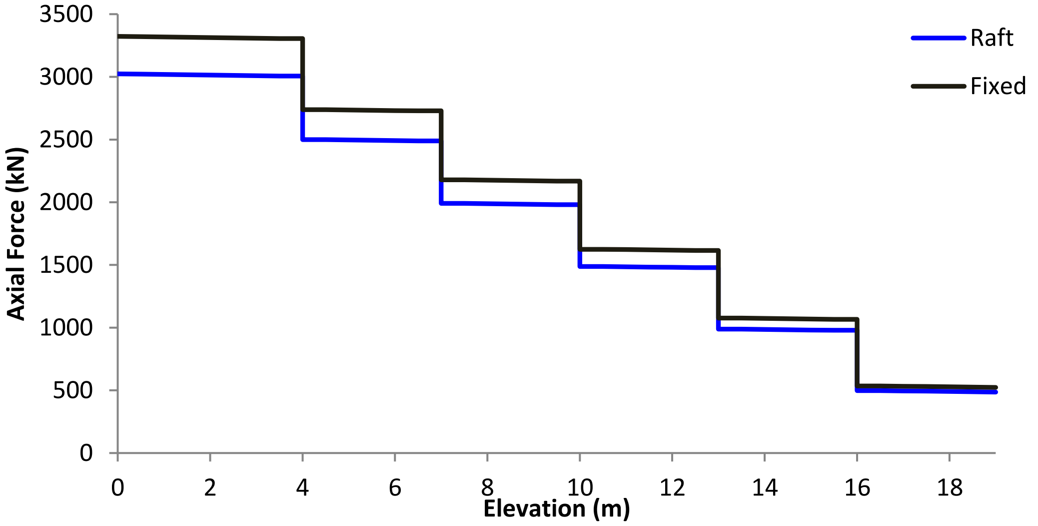


(c)

Fig. 11. Column axial force for 6-storey building: (a) corner column, (b) edge column, (c) interior column

Table 7. Column axial force results

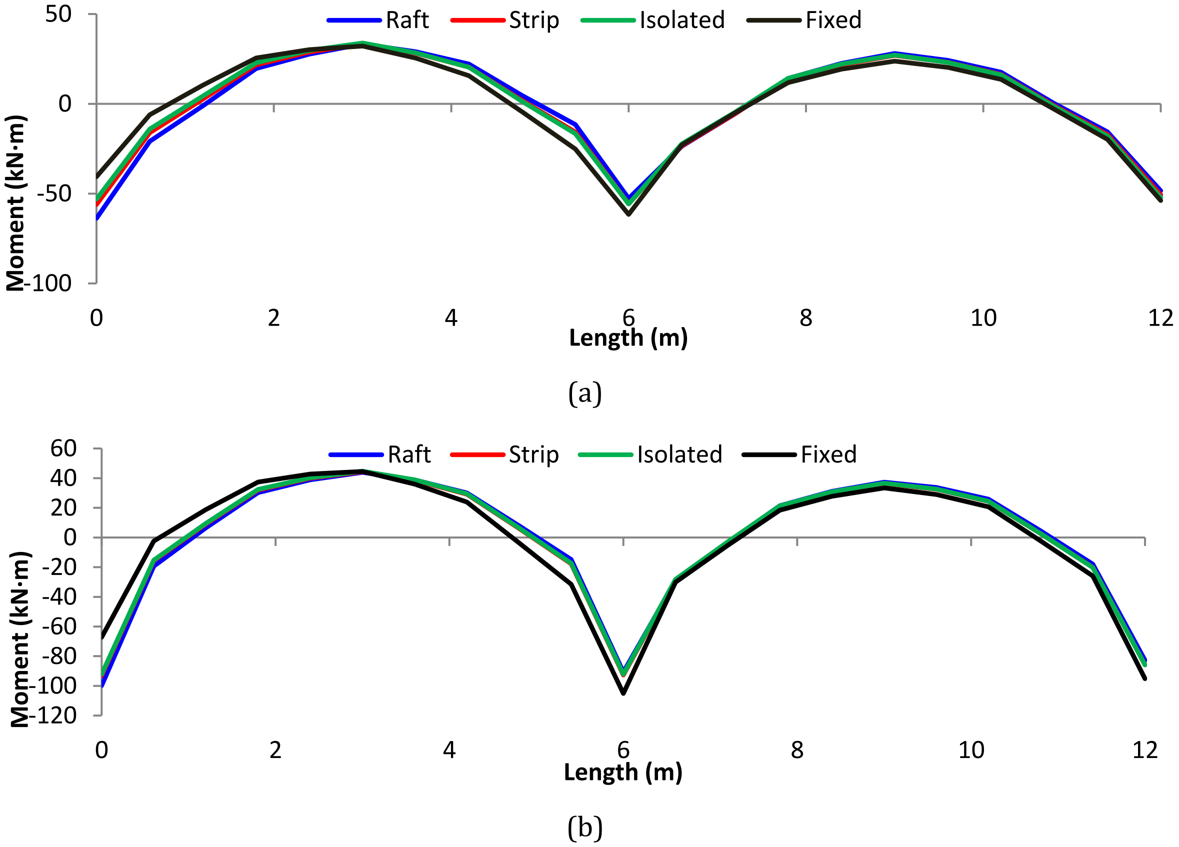
No. of storey	Support condition	Corner column (kN)	Edge column (kN)	Interior column (kN)
2-storey	Fixed	250.82	532.71	1188.5
	Isolated	272.36	557.4	1113.3
	Strip	274.95	558.76	1116.93
	Raft	288.51	560.41	1112.68
4-storey	Fixed	525.78	1093	2306.2
	Strip	677.26	1187	2078.6
	Raft	693.99	1167.9	2111.2
6-storey	Fixed	904.75	1725.4	3322.7
	Raft	1240.57	1855.89	3023.83

For the 6-storey building, the highest effect of soil interaction with the structure was observed under the raft foundations, resulting in increases of 37.11% in the corner columns and 7.6% in the edge columns, while the interior column forces decreased by approximately 9%. The variations in axial forces between exterior and interior columns are related to soil–foundation interaction, where differential settlement leads to greater settlement under interior columns. This behavior can be interpreted as result of the differential deformations under the columns support at foundations under the effects of loads in which relative displacements between columns occur due to soil deformation. This interaction leads to redistribution of vertical loads between the columns in a multi-storey building, altering the values of the calculated axial forces assuming that the soil is rigid and non-deformable. The results also show that the influence of soil–foundation interaction on axial force decreases with increasing storey level, where lower floors are more affected than upper floors due to the higher load transfer near the foundation level.

5.3. Bending Moment

Soil-foundation interaction directly affects the moment values developed in beams under static loads, resulting in a difference in moment distribution compared to the conventional model that assumes fixed ends at base. Soil elasticity leads to a redistribution of loads between horizontal and vertical elements, which in turn affects the beam's ability to withstand positive and negative moments. The variations of bending moment in the beams of the buildings are presented in Figs. 12-14 and summarized in Table 8.

Table 8 and Figs. 12-14 illustrate the bending moment variations in beams under fixed and flexible foundation conditions for different building heights. For a 2-storey building, the negative bending moment increased by approximately 30.7%, 38.3%, and 57% in the exterior beams of isolated, strip, and raft foundations, respectively. Interior beams recorded increases ranging from 37% to 48.4%, while positive bending moments increased from 13.4% to 17.7% in exterior beams and from 8.7% to 11.6% in interior beams. For a 4-storey building, the negative bending moment increased by approximately 99.3% for strip foundations and 107% for raft foundations in the exterior beams, while interior beams showed increases ranging from 68% to 75%. Positive moments increased by approximately 30% in the exterior beams and by between 19.7% and 20.7% in the interior beams. In the 6-storey building, the strongest effect of soil-foundation interaction was observed beneath the raft foundations, with negative moments increasing by approximately 105% in the exterior beams and by approximately 63.4% in the interior beams, while positive moments increased by approximately 17.9% and 9.9%, respectively. The variation of moments in beams by considering soil-foundation interaction results from soil deformation under loads that leads to a change in the distribution of displacements and rotations at the supports on which the beams rest. Thus, the supports do not remain as fixed as in fixed base conditions, causing a change in the load and bending patterns within the beams and resulting in a difference in the bending moment values from those calculated assuming the soil is rigid and non-deformable.



(a)

(b)

Fig. 12. Beam moment for the 2-storey building: (a) exterior beam, and (b) interior beam

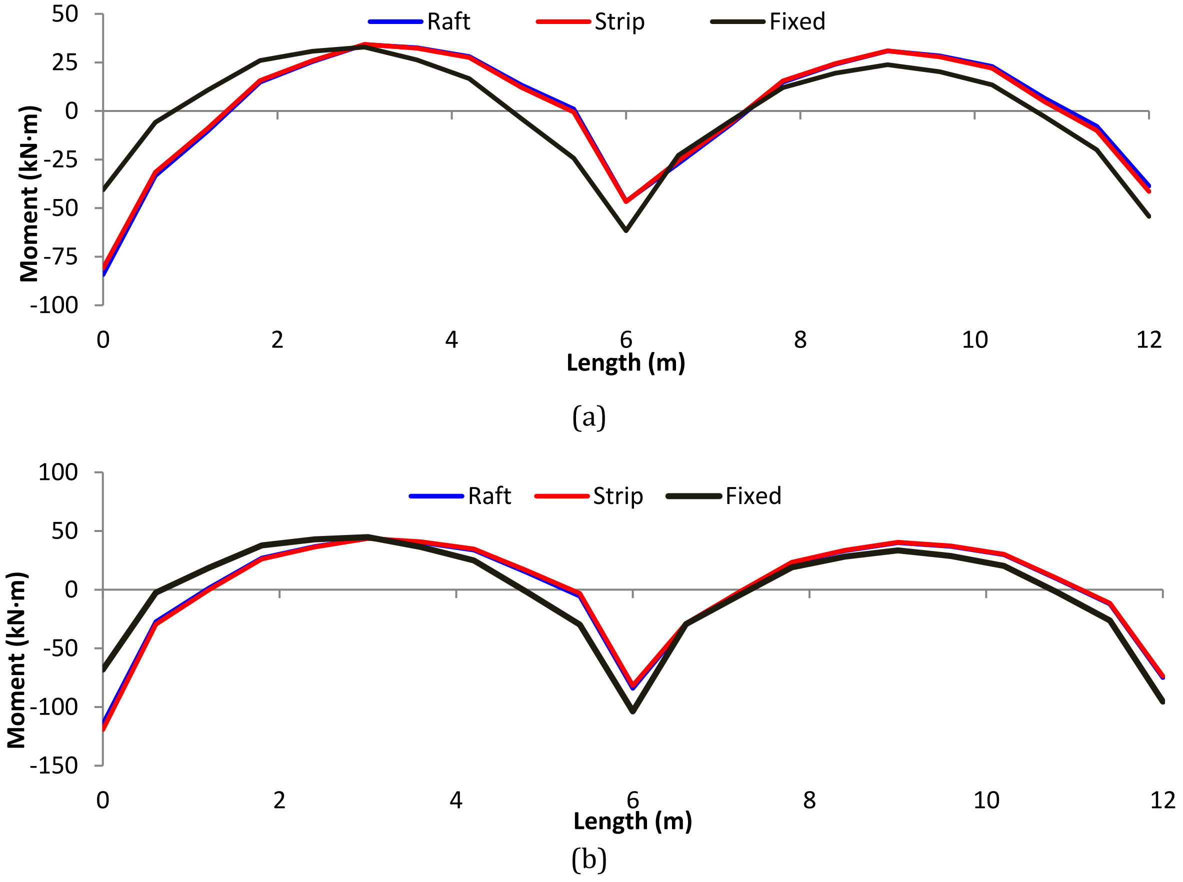


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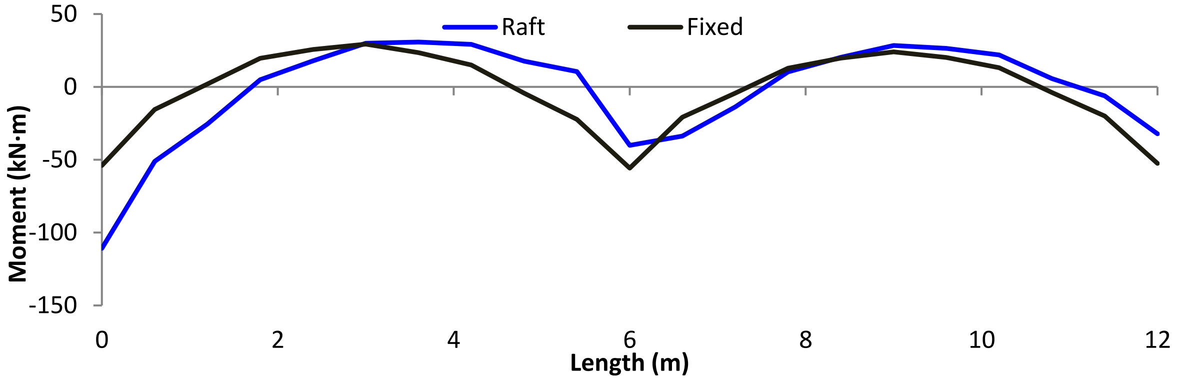
Fig. 13. Beam moment for 4-storey building: (a) exterior beam, and (b) interior beam



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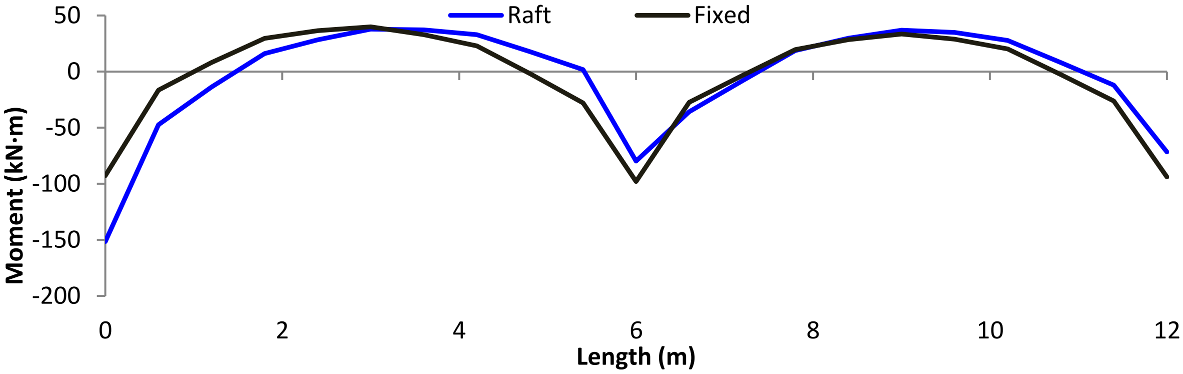


(b)

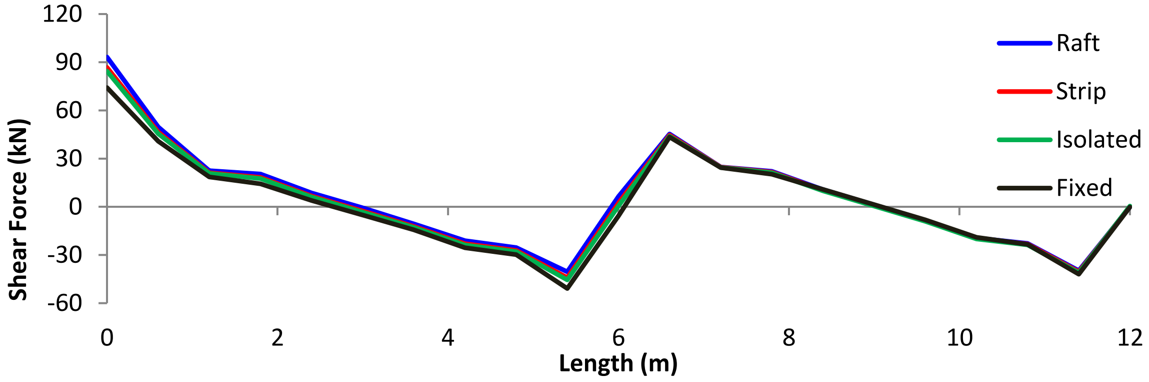
Fig. 14. beam moment for 6-storey building: (a) exterior beam, and (b) interior beam

Table 8. Beam bending moment results

No. of storey	Support condition	Exterior beam (-) (kN.m)	Exterior beam (+) (kN.m)	Interior beam (-) (kN.m)	Interior beam (+) (kN.m)
2-storey	Fixed	-40.56	23.76	-67.23	33.424
	Isolated	-53.02	27.12	-92.16	36.596
	Strip	-56.08	26.96	-93.08	36.35
	Raft	-63.73	27.99	-99.78	37.32
4-storey	Fixed	-40.59	23.8	-68.16	33.47
	Strip	-80.93	30.95	-119.25	40.41
	Raft	-84.18	30.92	-114.62	40.07
6-storey	Fixed	-54	24.05	-92.74	33.54
	Raft	-110.8	28.36	-151.57	36.87

5.4. Shear Force

Shear forces in beams are a fundamental factor that determine the behavior and safety of the structural system in multi-storey buildings. The shear response is one of the most important indicators of the efficiency of vertical and horizontal load transfer between structural elements. When considering soil-foundation interaction, it becomes clear that soil elasticity and deformation under static loads led to a change in the distribution of internal shear forces within the beams compared to fixed ends conditions. The variations of shear force in the beams of the buildings are presented in Figs. 15-17 and summarized in Table 9. Table 9 and Figs. 15-17 illustrate the variation in shear forces developed in beams under fixed and flexible foundation conditions for different building heights. For a 2-storey building, the shear forces in the exterior beams increased by approximately 13.9%, 16.9%, and 25.7% for isolated, strip, and raft foundations, respectively.



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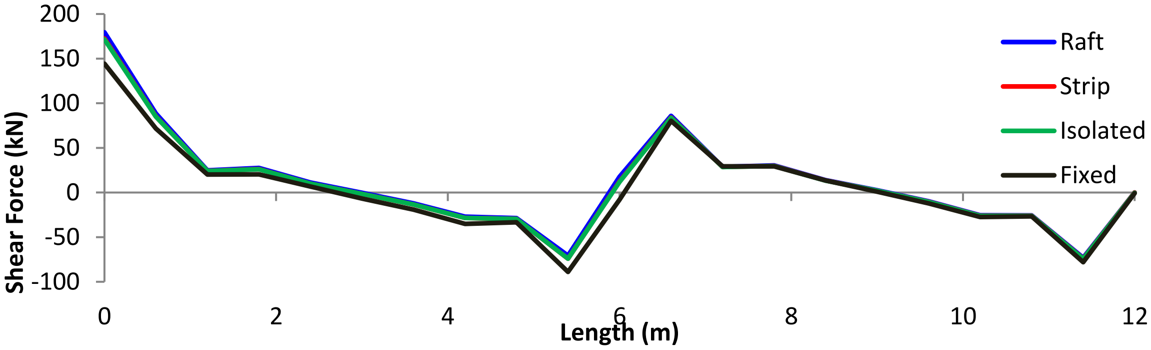

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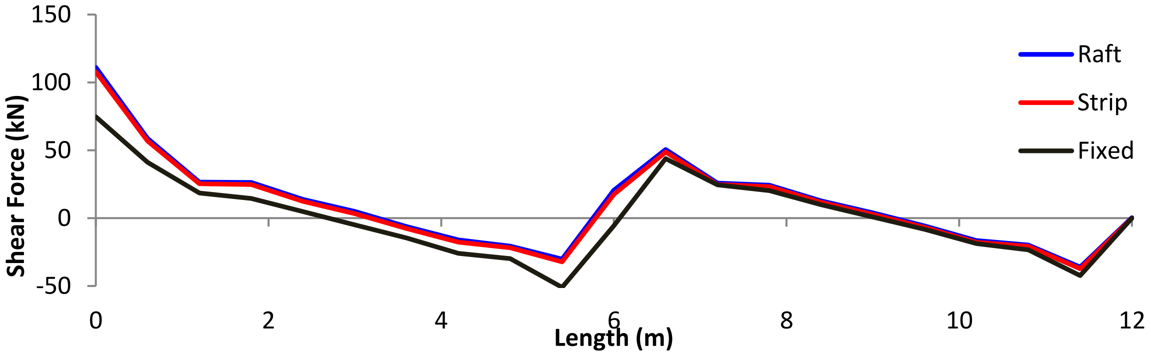
Fig. 15. Beam Shear force for 2-storey building: (a) exterior beam, and (b) interior beam



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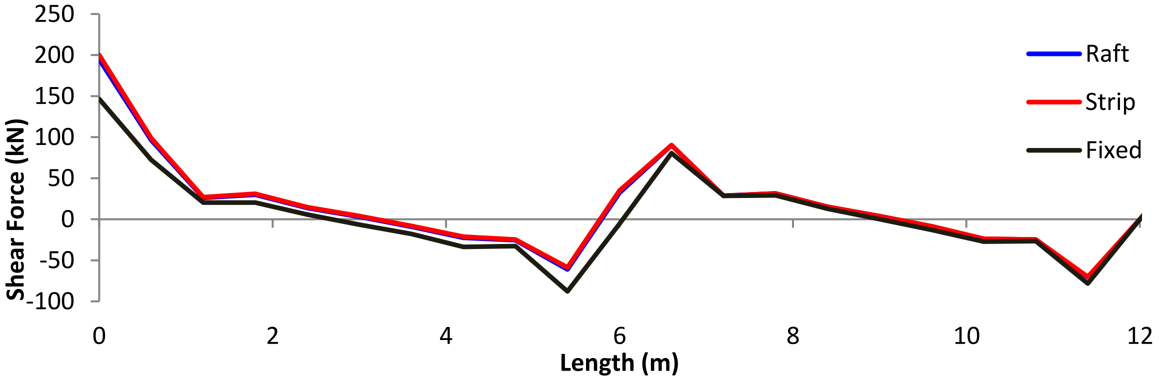

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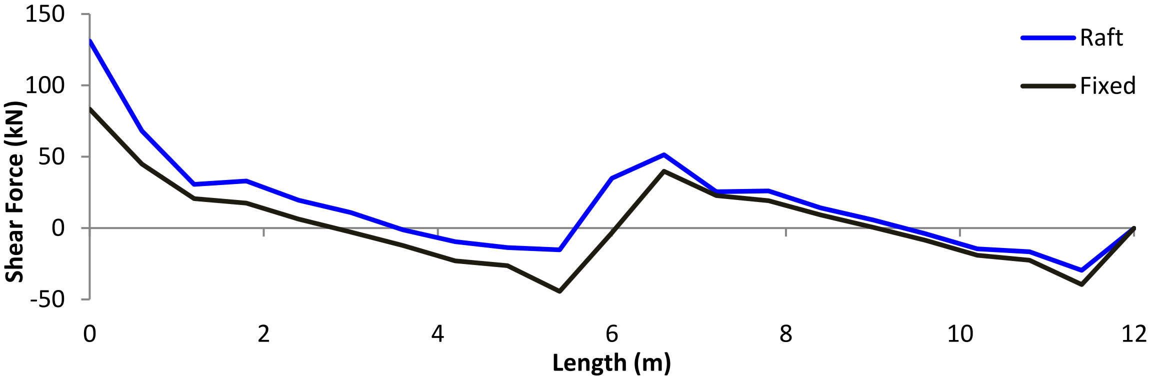
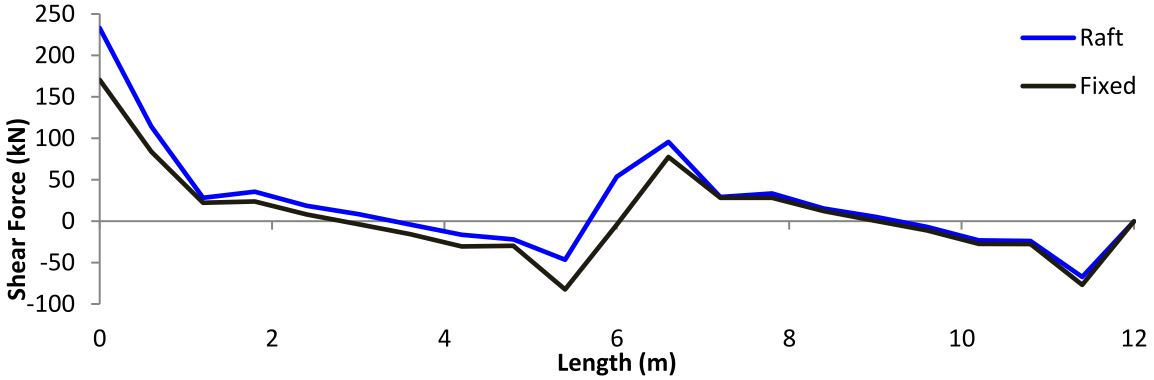
Fig. 16. Beam Shear force for 4-storey building: (a) exterior beam, and (b) interior beam



(a)



(b)

Fig. 17. Beam Shear force for 6-storey building: (a) exterior beam, and (b) interior beam

Table 9. Beam shear force results

No. of storey	Support condition	Exterior beam (kN)	Interior beam (kN)
2-storey	Fixed	74.18	144.36
	Isolated	84.46	171.62
	Strip	86.73	172.57
	Raft	93.21	179.47
4-storey	Fixed	74.68	146.47
	Strip	107.82	200.1
	Raft	111.08	194.68
6-storey	Fixed	83.35	170.49
	Raft	131.07	233.01

The shear forces in the interior beams also increased by approximately 18.9%, 19.5%, and 24.3%, respectively. For a 4-storey building, the shear forces in the exterior beams increased by approximately 44.4% for strip foundations and 48.7% for raft foundations, while the shear forces in the interior beams increased by approximately 36.6% and 32.9%, respectively. For the 6-storey building, the highest increase in shear forces on the beams was recorded under raft foundation conditions, where exterior and interior beams shear forces increased by approximately 57.2% and 36.7%, respectively. This behavior can be interpreted because the soil deformation under loading leads to a change in the relative displacements and deflections between the beam ends. This change causes a redistribution of internal loads within the beams, resulting in shear force values that differ from those obtained when assuming the soil is rigid and non-deformable.

6. Conclusion

In this study, buildings of different heights resting on Al-Akwat, Shat Al-Arab, Basra soil are analyzed considering soil-foundation interaction using finite element method with PLAXIS 3D software. The conclusions obtained from this analysis are:

- The results indicate that the type of foundation along with building heights have a significant effect on the internal forces of a building when compared to fixed base conditions. Shear forces, axial forces, and bending moments vary with the type of foundation and the height of the multi-storey building, highlighting the importance of considering soil-foundation interaction in the structural analysis and design for buildings constructed on layered silty clay soils, such as the soil of Al-Akwat, Shat Al-Arab, Basra.
- The results show that the raft foundation has the highest impact on the structural response due to the larger contact area and greater interaction with the underlying soil, resulting in greater maximum settlement and a more pronounced redistribution of loads compared to strip and isolated footings.
- Soil-foundation interaction influences load redistribution among columns. Axial forces in interior columns tend to decrease due to relatively larger settlements beneath them, whereas edge and corner columns experience increased axial forces.
- Exterior beams are more affected by soil-foundation interaction than interior beams, particularly in terms of both positive and negative bending moments and shear forces. This is due to non-uniform settlement, which causes larger rotations at exterior joints and leads to higher moments and shear compared to interior beams.
- For the 6-storey building with a raft foundation, relatively greater settlement was observed compared to the lower-rise buildings. This increased settlement significantly affects the structural response, leading to increased axial forces, bending moments, and shear forces in the structural members due to the soil-foundation interaction.

The results demonstrate the importance of considering soil-foundation interaction in the analysis of reinforced concrete multi-storey buildings. Particularly in buildings of 4 and 6 storeys in regions with soft silt layers, such as the middle zone of Basra city, where maximum settlement is significant and the moments developed in beam by more than double (107%). Therefore, when designing multi-storey buildings in such soil conditions, shallow foundations should be avoided or recommended to consider using soil improvement techniques or deep foundation systems, such as pile foundations, for high-rise buildings constructed on soft soil. This is essential to control excessive settlement and ensure that structural performance and serviceability requirements are adequately satisfied.

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