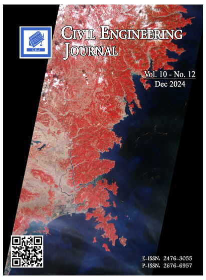
Available online at www.CivileJournal.org

Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 10, No. 12, December, 2024



Evaluation of Skirt-Raft Foundation Performance Adjacent to Unsupported Excavations

Balqees A. Ahmed [1*], Husam M. Saleh [2], Mina M. Jameel [3], Asmaa Al-Taie [4]

[1] *Department of Civil Engineering, College of Engineering, University of Baghdad, Baghdad, Iraq.*

[2] *Ministry of Construction and Housing, Baghdad, Iraq.*

[3] *Ministry of Education, Baghdad, Iraq.*

[4] *Institute for Sustainable Industries and Liveable Cities, Victoria University, Melbourne, Australia.*

Received 27 August 2024; Revised 17 November 2024; Accepted 25 November 2024; Published 01 December 2024

Abstract

The continuous demand for urban development, along with the construction of new buildings, highways, and infrastructure, creates an increasing necessity for excavation activities. Deep excavation near existing buildings can lead to ground instability, potentially causing structural damage to nearby properties. This research aims to investigate methods for enhancing buildings stability from the initial stages of construction, focusing on protecting structures from potential future adjacent excavations. This study utilizes a skirt-raft foundation system, modeled using the finite element software PLAXIS 3D, to evaluate its effectiveness in improving stability and protection. The study analyzed the behavior of raft foundations in clay soil adjacent to excavations ranging from 1 m to 10 m and compared this with the performance of raft foundations with added skirt foundations. The comparison focused on settlement, rotation, and lateral movement of the excavations to assess potential building damage. The results showed that incorporating a skirt foundation significantly enhanced structural stability and reduced excavation-related damage. The implementation of a skirt foundation to a depth of 0.5B (where B is the foundation width) for excavations of similar depth has been shown to significantly reduce damage levels from medium or high to light while also decreasing differential settlement by 80%. It is recommended that adjacent excavation depths should not exceed 0.25B. However, if a skirt foundation is constructed at a depth of 0.5B, the excavation depth can be safely extended to 0.75B.

Keywords: Excavations; Raft Foundation; Skirt Foundation; Clayey Soil; PLAXIS 3D.

1. Introduction

Rapid urban development, including the construction of high-rise buildings, highways, metro tunnels, and other modern infrastructure, often necessitates deep excavations to support these projects. However, excavation activities near existing and older buildings can significantly impact the stability of these structures, posing potential risks to their integrity [1-3]. Excavations can cause soil to become loose and experience lateral displacement, leading to a loss of stability in nearby buildings. This instability can result in structural failure and potential collapse, particularly if the buildings are unable to support the excavation sides or before support work is initiated. Several researchers have studied the effect of excavations on buildings and the subsequent damage that may occur [4-6]. The assessment of damage resulting from lateral displacement and foundation settlement has been thoroughly studied by Piciullo et al. [6]. Their research focuses on the effects of deep excavations related to foundational construction, employing various methods to analyze displacement and settlement while comparing their effectiveness.

---

* Corresponding author: balqees.a@coeng.uobaghdad.edu.iq

http://dx.doi.org/10.28991/CEJ-2024-010-12-018

The assessment of damage resulting from lateral displacement and settlement of the foundation has been thoroughly studied by Piciullo et al. [6]. Their research focused on the effects of deep excavations related to foundational construction, employing various methods to analyze displacement and settlement while comparing their effectiveness. The study focused on two buildings in Norway to predict both short- and long-term damage resulting from deep excavations near these structures. The results indicated significant damage, highlighting the critical impact of such excavations on building integrity. Numerical analysis was conducted by Khalid & Alshameri [7] on two mat foundations situated in two types of clay soil to study the safe horizontal distance between the first mat foundation and the excavation for the second mat foundation, as well as the optimal excavation depth. The results showed that the most effective depth-to-horizontal distance ratio was 1:3. Additionally, the findings revealed that the factor of safety increases as the distance between the building and the excavation increases and the weight of the building decreases.

The extent of damage is directly related to the soil deformation caused by excavation activities. Soil deformation is typically categorized into two types: short-term and long-term. The short-term deformation is influenced by several factors, including the depth of the excavation, the proximity of the building to the excavation site, the soil type, the weight and structure of the building, and the characteristics of the retaining system used. In contrast, long-term deformation is primarily governed by changes in groundwater levels and consolidation settlement processes [6]. Many experimental and numerical studies have adopted the short-term model for analyzing the excavation results [7-10].

The main causes of building damage resulting from adjacent excavations include differential settlement, angular distortion of the structure, and lateral soil movement [6-10]. Figure 1 shows Bjerrum's limits for angular distortion [11], with angular distortion adopted as the main factor for controlling damage.

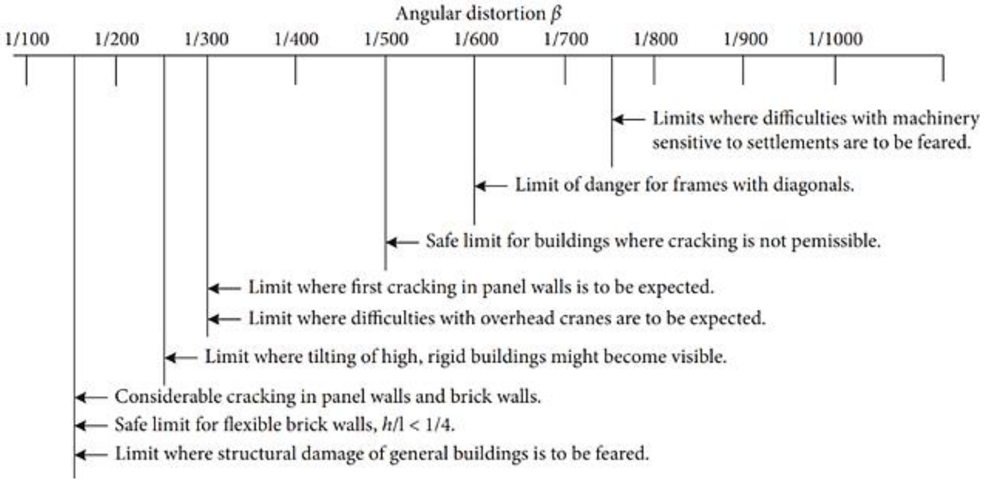


Figure 1. Limiting angular distortion [11]

The impact of new deep excavations on adjacent buildings and underground metro tunnels [12] was investigated through numerical modeling, accurately reflecting the real geometric dimensions. This study focused on analyzing the horizontal displacement and settlement of the building, as well as the surface settlement and deformation of the metro tunnel. While shallow excavations generally have negligible effects, deep excavations present significant risks, making it essential to employ a layered excavation approach with proper excavation support to mitigate potential damage.

The primary cause of building damage is the lateral movement of soil resulting from unsupported excavation. This lateral movement induces differential settlement of the foundation, leading to foundation distortion, potential lateral collapse of the excavation, and ultimately, structural damage to the building. Proper support systems are essential to prevent such failures and ensure stability during excavation activities [13-16]. Through research on the impact of excavation work on nearby buildings, Rankin [17] proposed a classification system for the level of damage resulting from these excavations, dividing it into four distinct categories. Each category reflects the severity of the damage, ranging from negligible to high. The first and second categories indicate that the building is not significantly affected by the excavation, with damage levels considered minimal and within acceptable limits.

Numerous numerical, theoretical, and experimental studies [18-34] have demonstrated the damage caused by nearby excavations, whether supported or unsupported, especially in deep excavations with inadequate support, leading to lateral displacement and differential settlement. Previous studies have documented numerous instances of building collapses caused by deep excavations adjacent to the structures, particularly when these excavations lacked adequate support or were insufficiently reinforced. To address this critical issue, this research proposes the integration of a skirt foundation beneath the raft foundation. This design aims to significantly enhance the foundation's performance by improving settlement control and increasing its bearing capacity, thereby mitigating the risks associated with adjacent deep excavations.

The primary objective is to minimize the impact of neighboring excavations on buildings in the future. A skirt foundation, which is a skirt-shaped structure designed to confine the soil within its boundaries, plays a crucial role in enhancing the stability of the building. This foundation type was chosen due to extensive research highlighting its effectiveness in improving structural stability. Several studies have demonstrated the importance of adding a skirt foundation in increasing the resilience and overall performance of buildings, especially in environments where deep excavations present significant risks [35-40].

2. Research Methodology

Figure 2 shows the flow chart outlining the research methodology designed to achieve the objectives of this study. The primary aim of this paper is to evaluate the performance of skirt-raft foundations located adjacent to unsupported excavations in clay soil.

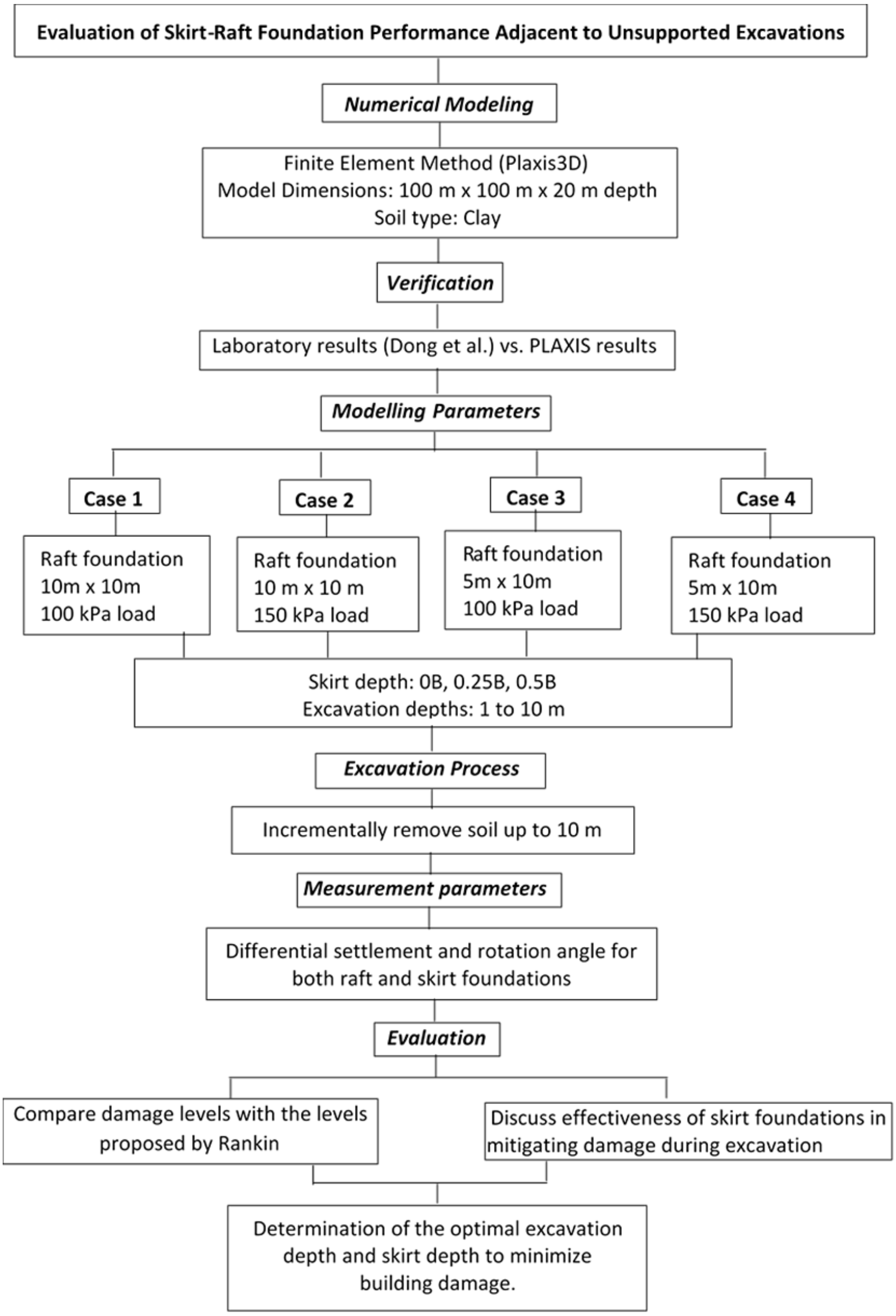


Figure 2. The research methodology

The damage assessment for raft-skirt foundations is conducted by analyzing differential settlement values and rotation angles. These parameters are then compared to the thresholds proposed by Rankin [17] as shown in Table 1. Each damage level in Table 1 is represented by a specific color: green indicates a negligible level of damage, blue corresponds to light damage, orange represents moderate damage, and red signifies a high level of damage. These color-coded levels are explained by the extent of damage caused by differential settlement and rotation for the building. The research was conducted, and the results were analyzed under the following conditions:

1. Skirt foundation length did not exceed 0.5B for cost-effectiveness,
2. Short-term soil deformation was assessed,
3. Clayey soil was the focus of the study,
4. Excavation was adjacent to the building,
5. The excavation was unsupported.

Table 1. Typical values of maximum building slope and settlement for damage risk assessment

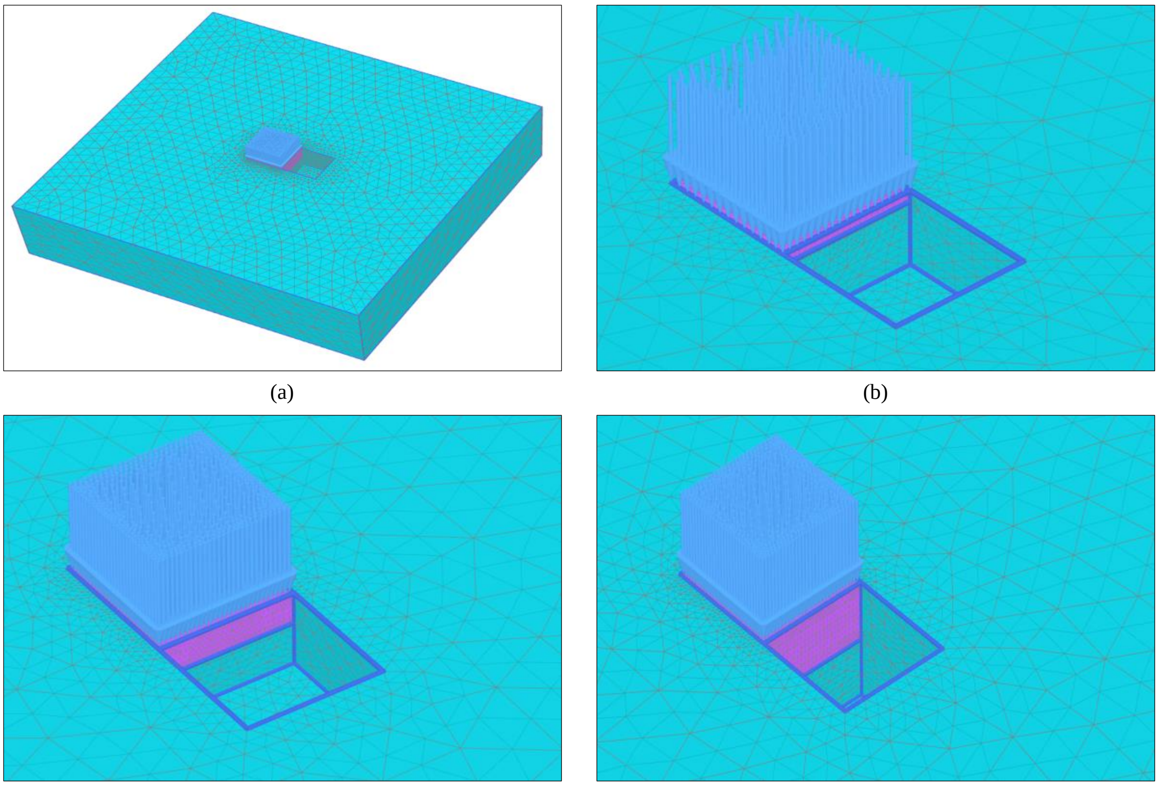
Risk level	Max. angle of rotation ($\boldsymbol{\theta_{max}}$)	Max. tilt ($\boldsymbol{\Delta\delta_V mm}$)	Level of damage
1	$< \frac{1}{500}$	< 10	**Negligible**: (superficial damage unlikely)
2	$\frac{1}{500} - \frac{1}{200}$	10-50	**Light**:(Possible superficial damage which is unlikely to have structural significance)
3	$\frac{1}{200} - \frac{1}{50}$	50-75	**Moderate**: (Expected superficial damage and possible structural damage to buildings, possible damage to relatively rigid pipelines)
4	$> \frac{1}{50}$	> 75	**High**: (Expected structural damage to buildings. Expected damage to rigid pipelines, possible damage to other pipelines)

3. Numerical Modeling

Numerical modeling for this case was performed using the finite element method through one of the important geotechnical engineering programs (PLAXIS 3D). The model's dimensions were 100×100 m with a depth of 20 m. The soil used in the modeling was clayey soil, with samples collected from the Zayuna site in Baghdad following comprehensive soil investigations. The soil properties, determined through experimental testing, are presented in Table 2. The Hardening model was used to simulate the soil behavior, as it is particularly well suited for representing excavations due to its ability to accurately capture soil behavior under stress [2]. The skirt and the raft were modeled using the Linear Elastic model, as shown in Table 2. The thickness of the raft used was 70 cm, and the width of the skirt was 20 cm. Two types of foundations were used: the first was a raft foundation with dimensions of 10 × 10 m, and the second was 10 × 5 m. The applied loads were simulated based on actual building loads, ranging from 100 kPa (10 ton/m²) to 150 kPa (15 ton/m²). The skirt lengths used in the analysis were 0.25B - 0.5B. The excavation was modeled using the volume element of the soil adjacent to the building. The excavation process was carried out in ten stages, with 1 m of soil removed in each stage. Figure 3-a shows a general 3D model of the study, while Figure 3-b shows the case without a skirt. Figures 3-c and 3-d present foundations with skirts at depths of 0.25B and 0.5B, respectively. The main purpose of the skirt is to enclose the soil under the raft foundation, reducing both differential settlement and the lateral movement of the soil. The current study focuses on three main outcomes, measured using the PLAXIS program, as shown in Figure 4. Figure 4-a represents a cross-section of the skirt foundation. It was noted that the differential settlement ($\Delta\delta_v$ mm) was measured at a position within the circle located at the corner of the right raft, as shown in Figure 4-b. While the lateral movement was measured on the side of the excavation adjacent to the building, as demonstrated in Figure 4-c.

Table 2. Soil properties used in modeling

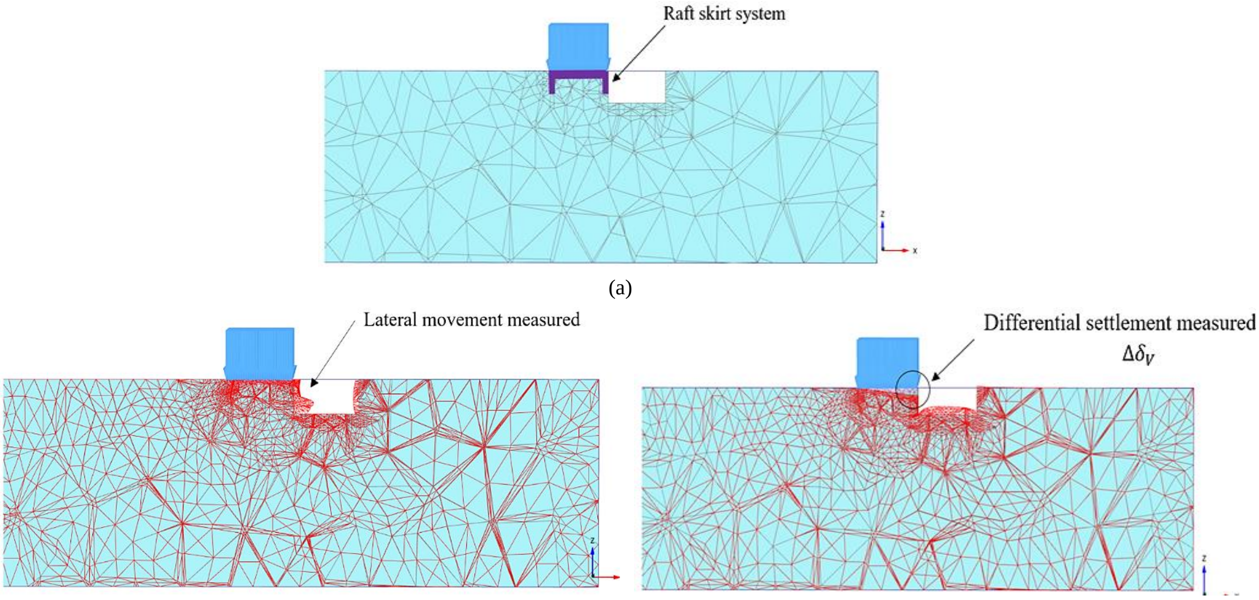
Case	Clay soil	Footing	Skirt
Material model	Hardening	Liner elastic	Liner elastic
Drainage type	Undrain	Non porous	Non porous
Unit weight (kN/m^3)	17	24	24
C.c	0.14	-	-
C.s	0.038	-	-
E (kN/m^2)	-	23500000	23500000
V'	-	0.3	0.3
C′ (kPa)	50	-	-



(a) (b)

(c) (d)

Figure 3. Geometry modelling of problem (a) general model (b) raft without skirt, (c) Raft with skirt 2.5 m and (d) raft with skirt 5 m



(a)

(b) (c)

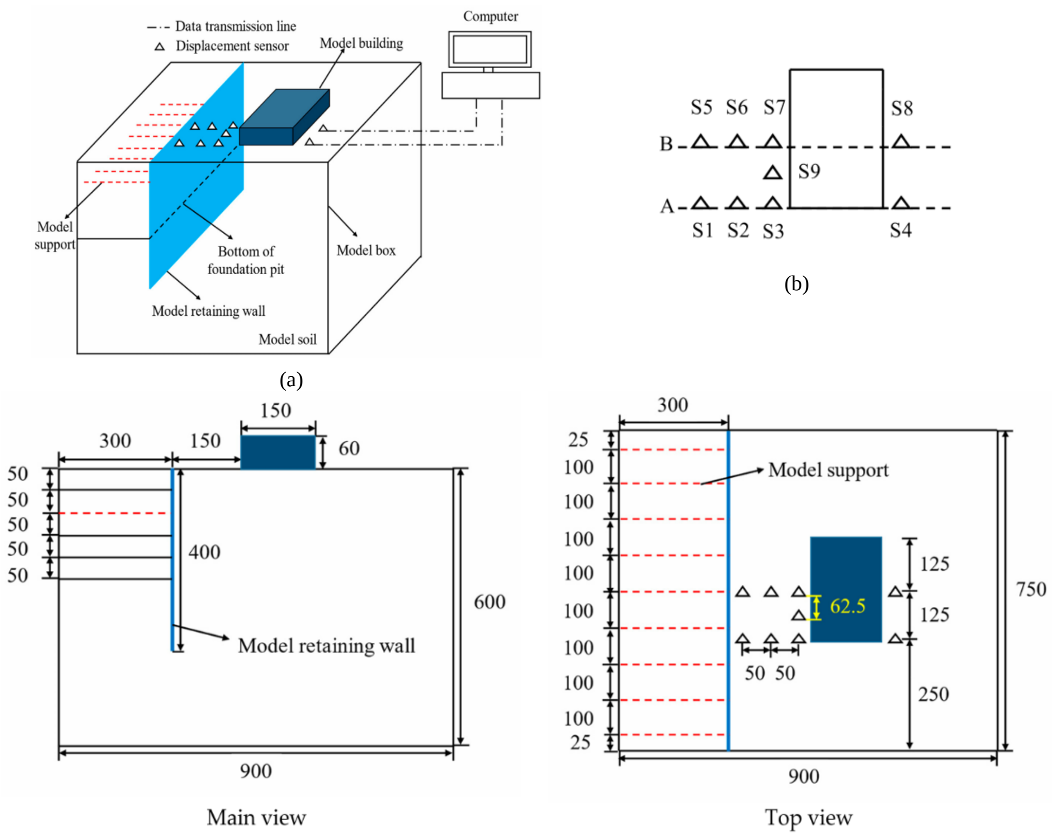
Figure 4. Section plan (a) raft with skirt, (b) Position of differential settlement (c) Position of maximum of lateral movement

4. Verification

To verify the performance of the PLAXIS program in simulating excavations adjacent to buildings, a comparative analysis was conducted between the laboratory results obtained by Dong et al. [2] and those obtained from PLAXIS 3D. A building adjacent to excavations supported by a retaining wall was used in the study. The building was modeled using a steel plate, while the retaining wall was represented by an aluminum plate. The properties are detailed in Table 3 and Figure 5. The soil was modeled with the Mohr-Coulomb model, while both the building and retaining wall were represented using the linear elastic model. The excavation was carried out in stages, each 50 mm in depth. Nine sensors were arranged, as shown in Figure 5, to measure the settlement caused by the excavations. The sensors were distributed around the building and along the distance between the building and the excavation site. The data from sensors S1, S2, S3, and S4 were used to validate the model employed in the study.

Table 3. Material properties after Dong et al. [2]

An example of a column heading	Weight Density γ (kN/m^3)	Elastic Modulus E_0 (MPa)	Poisson's Ratio (μ)	Cohesion c (kPa)	Internal Friction Angle ϕ
Soil	16.45	37.9	0.3	2.7	35.5
Retaining wall	27.02	68,000	0.32	-	-
Steel	78.5	210,000	0.3	-	-



(a)

(b)

(c)

Figure 5. Schematic of the model group of tests (a) Model details, (b) Sensor locations relative to the building, (c) The main and top view of the model [2]

The results, shown in Figure 6, illustrated the sensor reading at each excavation stage and various distances from the foundation pit. The results showed that the values obtained and the behavior observed were consistent between the PLAXIS 3D program and the laboratory results prepared by Dong et al. [2]. It was observed that as the distance from the building decreased, the monitored settlement gradually reduced. However, the total change in settlement across the monitored surface increased progressively as the depth of the excavation

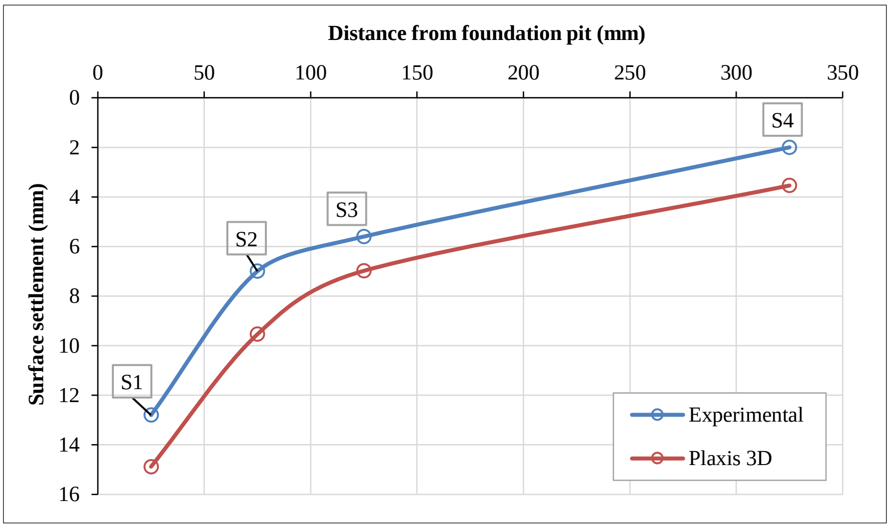


Figure 6. Comparison between experimental results and PLAXIS 3D results

5. Program of Modeling

A total of 120 cases were performed, divided into two main groups. Each group had different dimensions for the raft foundations: the first was 10×10 m and the second was 5×10 m, with the 10 m side adjacent to the excavation, as shown in Table 4. Each main group was further divided into two secondary groups, with each secondary group subjected to different loads, comprising 30 cases each. The 30 cases in each secondary group were then divided into three sets, each involving excavations adjacent to the building. The excavations began at a depth of 1 m, with the subsequent cases increasing in depth by 1 m at each stage until reaching a total depth of 10 m. The second set of models repeated the condition of the first set but included a skirt foundation added to the raft foundation at a depth of 0.25B. This was followed by a repetition of the first set of models, with the skirt foundation extended to a depth of 0.5B m. The geotechnical analysis of the problem was carried out according to the structural analysis and building loads. The final stresses applied to the raft foundation were considered in the evaluation. Two building configurations were adopted: a five-storey building with a load of 2 tons/m^2 and a seven-storey building with a load of 2 tons/m^2, plus a small additional storage area on the roof.

Table 4. Program of modeling

Raft Foundation Area (B×L)	Building Weight	Depth of Skirt	Depth of Excavation (m)									
10×10 (m×m)	**(Case 1)** 100 kPa	0B	1	2	3	4	5	6	7	8	9	10
		0.25B	1	2	3	4	5	6	7	8	9	10
		0.5B	1	2	3	4	5	6	7	8	9	10
	(Case 2) 150 kPa	0B	1	2	3	4	5	6	7	8	9	10
		0.25B	1	2	3	4	5	6	7	8	9	10
		0.5B	1	2	3	4	5	6	7	8	9	10
5×10 (m×m)	**(Case 3)** 100 kPa	0B	1	2	3	4	5	6	7	8	9	10
		0.25B	1	2	3	4	5	6	7	8	9	10
		0.5B	1	2	3	4	5	6	7	8	9	10
	(Case 4) 150 kPa	0B	1	2	3	4	5	6	7	8	9	10
		0.25B	1	2	3	4	5	6	7	8	9	10
		0.5B	1	2	3	4	5	6	7	8	9	10

Excavations adjacent to the building pose a danger to the building because the progress of excavation causes settlement in the raft foundations on the side adjacent to the excavation. This leads to differential settlement and rotation of the foundations, which affects the stability of the building [17]. Figure 7 shows the basic criteria used to evaluate the extent of the damage to the building as a result of nearby excavation work. These criteria include the differential settlement and rotation angle of the building, which were adopted to obtain the final results. These results were then discussed by comparing them with the cases presented in Table 1 by Rankin [17].

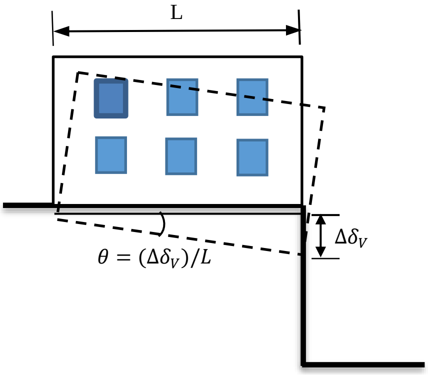


Figure 7. Parameters of building damage for level assessment

6. Results and Discussion

Two main components were used for the analysis. The first involved calculating the relationship between differential settlement and angle of rotation with depth of excavation and discussing the improvement rate in differential settlement and lateral displacement on the excavation side when the skirt foundation was included. The second component evaluated the extent of damage to the building as a result of adjacent excavations, both with and without the skirt foundation, by comparing the results with values in Table 1.

6.1. Case 1

The first case involved a raft foundation with dimensions of 10×10 m, carrying a load of 100 kPa, with the excavation progressing to a depth of 1 m adjacent to the building. This was carried out without the presence of a skirt foundation for the first group, with a skirt at a depth of 0.25B (2.5m) for the second group, and with a skirt at a depth of 0.5B (5m) for the third group. The following aspects were studied:

6.1.2. Variation of Differential Settlement and Rotation Angle with Addition of Skirt Foundation

As shown in Figures 8 and 9, the progress of excavation, starting from 1 m to 10 m, significantly affects differential settlement. However, with the addition of the skirt foundation at a depth of 0.25B (2.5m), there was a noticeable reduction in the rate of differential settlement and lateral movement at depths of 2, 5, and 10 m by 72%, 48%, and 32%, and by 52%, 29%, and 11%, respectively. By increasing the depth of the skirt to 0.5 B (5m), the reductions in differential settlement and lateral movement were 96%, 82%, 57%, and 69%, 70%, and 33%, respectively.

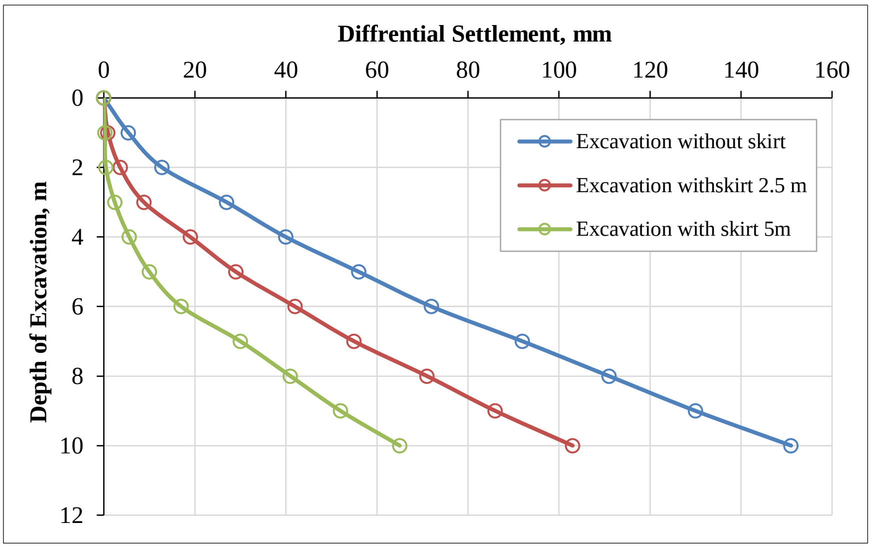


Figure 8. The change in differential settlement with increasing depth of excavation for Case 1

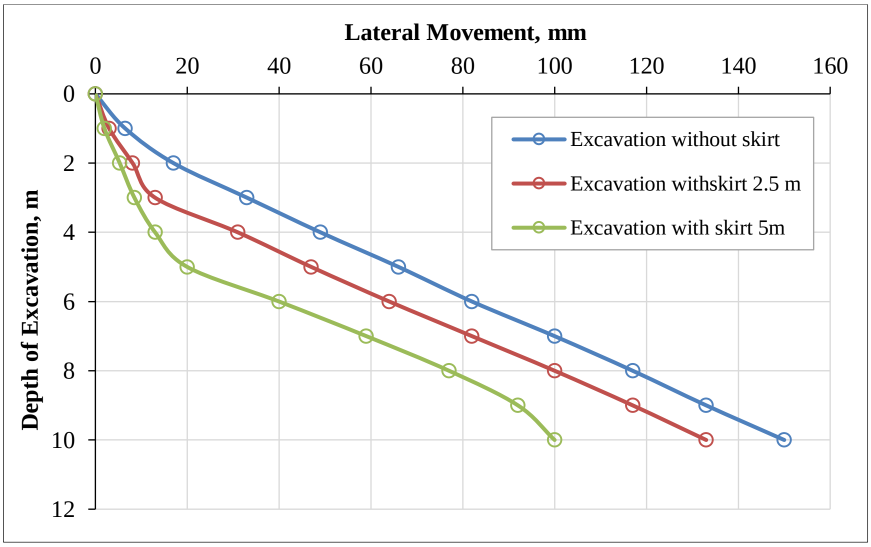
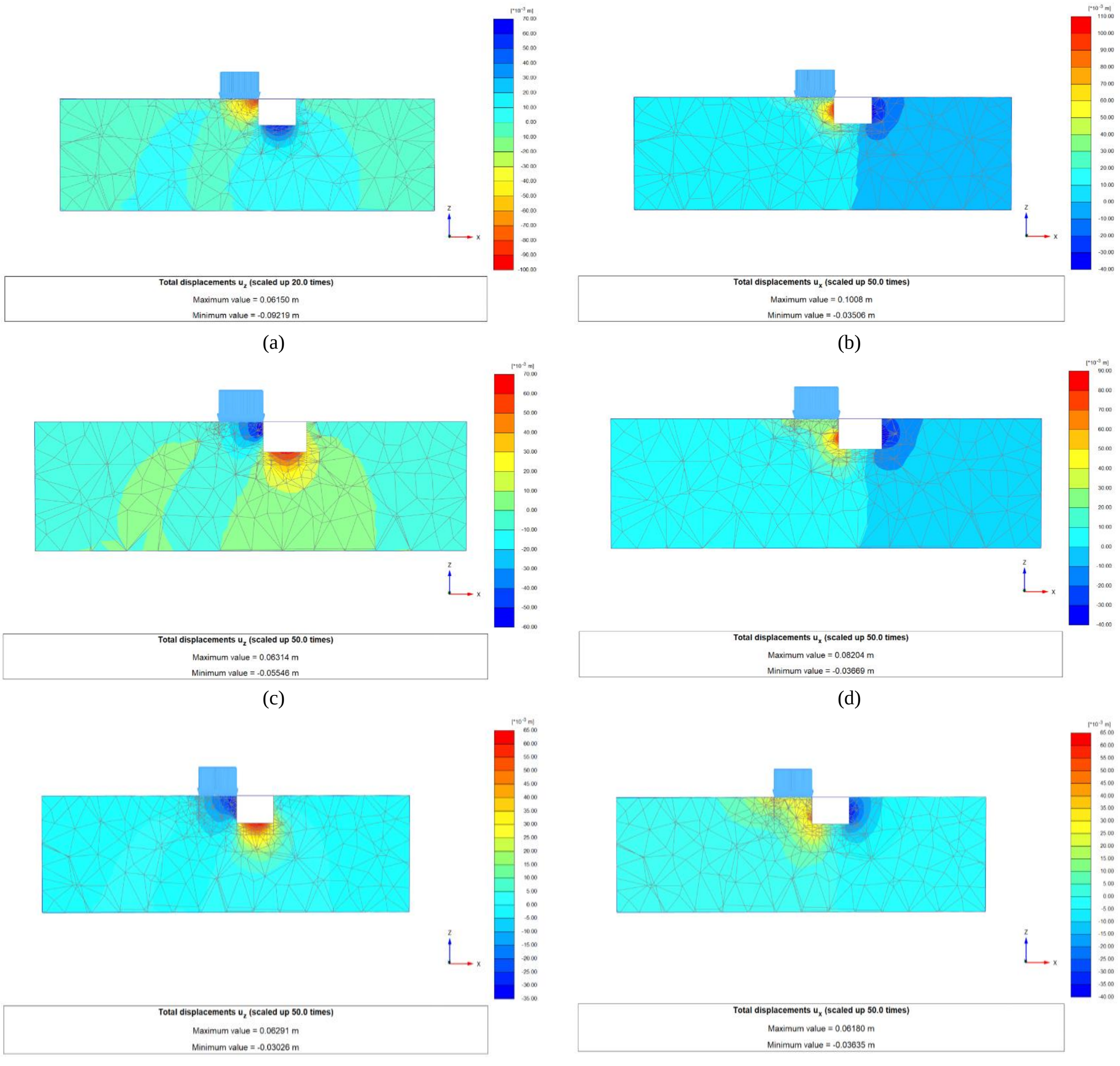


Figure 9. The change in lateral displacement with increasing excavation depth for Case 1

Figure 10 illustrates the contour values of settlement and lateral displacement for the foundation in the first case. It is evident that the highest settlement values occur at the corner of the foundation closest to the excavation. Negative contour values indicate the expected settlement beneath the foundation due to the excavation work, while positive contour values signify upward soil movement, particularly in the excavated area. Regarding lateral displacement, positive contour values represent soil movement to the right, indicating lateral movement beneath the foundation, whereas negative contour values show soil movement to the left, away from the foundation and towards the excavation area. The contour values presented correspond to a depth of 7 m, demonstrating the behavior of the skirt foundation at a depth greater than the maximum skirt depth of 5 m. The improvement percentage of differential settlement and lateral movement is shown in Figures 11 and 12.



(a) (b)

(c) (d)

(e) (f)

Figure 10. Section contours of case 1 (a) differential settlement of raft without skirt (b) lateral displacement of raft without skirt (c) differential settlement of raft with skirt 0.25B (d) lateral displacement of raft with skirt 0.25B (e) differential settlement of raft with skirt 0.5B (f) lateral displacement of raft with skirt 0.5B.

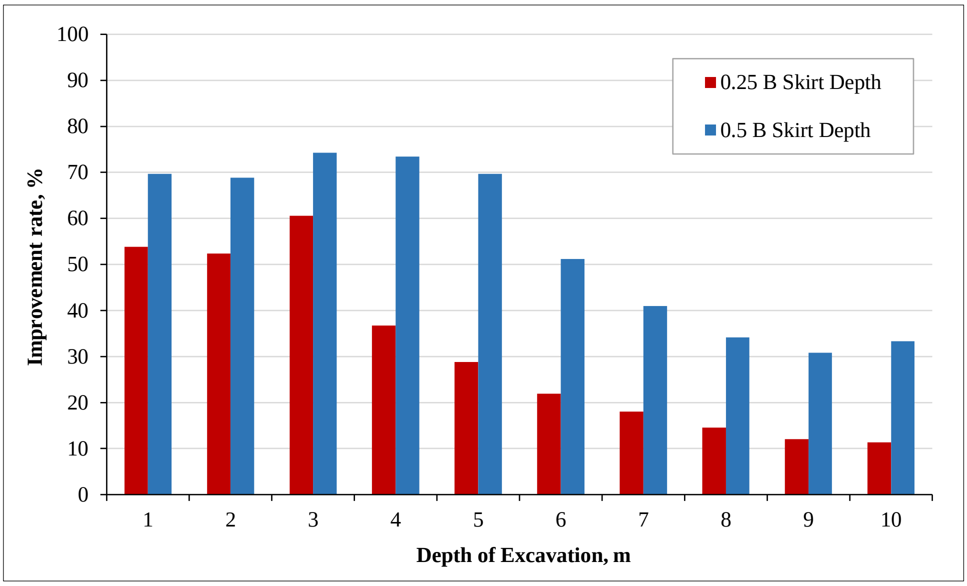


Figure 11. Percentage of differential settlement improvement after adding the skirt foundation for Case 1

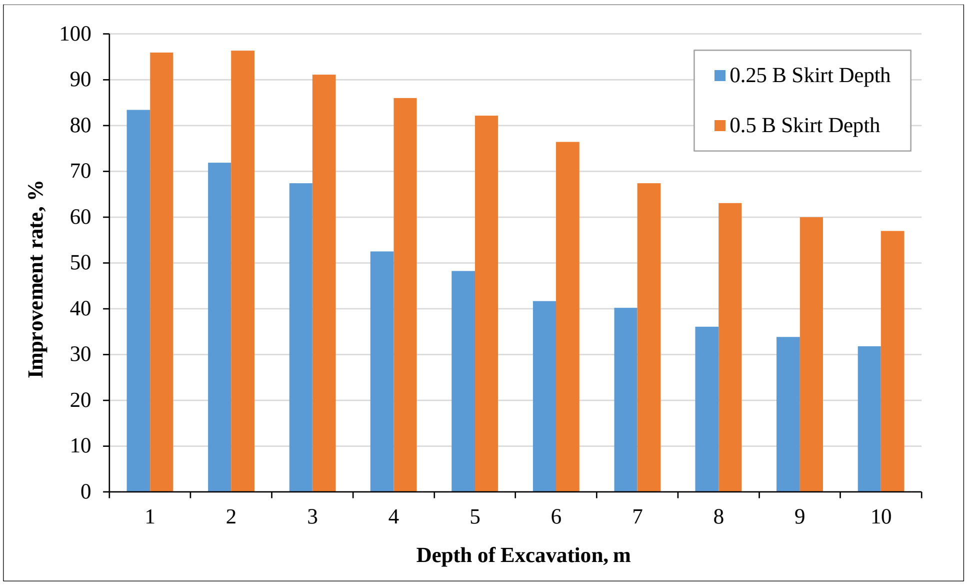


Figure 12. Percentage of lateral movement reduction after adding the skirt foundation for Case 1

6.1.2. Level of Damage Caused by Adjacent Excavations

To evaluate the damage to the building as a result of adjacent excavations, a comparison was made between the results obtained for the differential settlement and rotation angle, and the range of these parameters was used to evaluate the damage levels in Table 1. The results were presented in Table 5.

Table 5. The degree of damage to the building under the effect of a load of 100 kPa (dimension of raft foundation 10×10 m)

Excavation Depth(m)	Without skirt			With skirt (0.25B)			With skirt (0.5B)		
	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level
1	5.42	0.000542	Negligible	0.9	0.00009	Negligible	0.22	0.000022	Negligible
2	12.8	0.00128	Light	3.6	0.00036	Negligible	0.47	0.000047	Negligible
3	27	0.0027	Light	8.8	0.00088	Negligible	2.4	0.00024	Negligible
4	40	0.004	Light	19	0.0019	Light	5.6	0.00056	Negligible
5	56	0.0056	Moderate	29	0.0029	Light	10	0.001	Light
6	72	0.0072	Moderate	42	0.0042	Light	17	0.0017	Light
7	92	0.0092	High	55	0.0055	Moderate	30	0.003	Light
8	111	0.0111	High	71	0.0071	Moderate	41	0.0041	Slight
9	130	0.013	High	86	0.0086	High	52	0.0052	Moderate
10	151	0.0151	High	103	0.0103	High	65	0.0065	Moderate

The findings showed that the same building could exhibit different damage levels depending on whether it was evaluated based on differential settlement or rotation angle. Therefore, the impact level reflected the worst-case scenario. The most serious factor that needed attention was the differential settlement factor [6]. As noted in Table 5, the level of damage was moderate at an excavation depth of 5 m and reached high at 7 m. However, when a skirt foundation with a depth of 0.25 B was used, the high damage level extended to 9 m. When the skirt depth reached 0.5 B, the depth of the danger exceeded 10 m.

6.2. Case 2

In Case 2, the dimensions of the raft foundation were the same as in Case 1 (10×10 m), but the load was heavier, at 150 kPa. The depth of the skirt foundation was either 0.25B (2.5m) or 0.5B (5m), with 10 cases of graduate excavation. The results were as follows:

6.2.1. Variation of Differential Settlement and Rotation Angle with Addition of Skirt Foundation

The results of differential settlement and lateral movement with graduated excavation depth are shown in Figures 13 and 14. The results showed that the differential settlement was 384 mm, which was greater than the 151 mm observed in Case 1 at a depth of 10 m due to the heavier load.

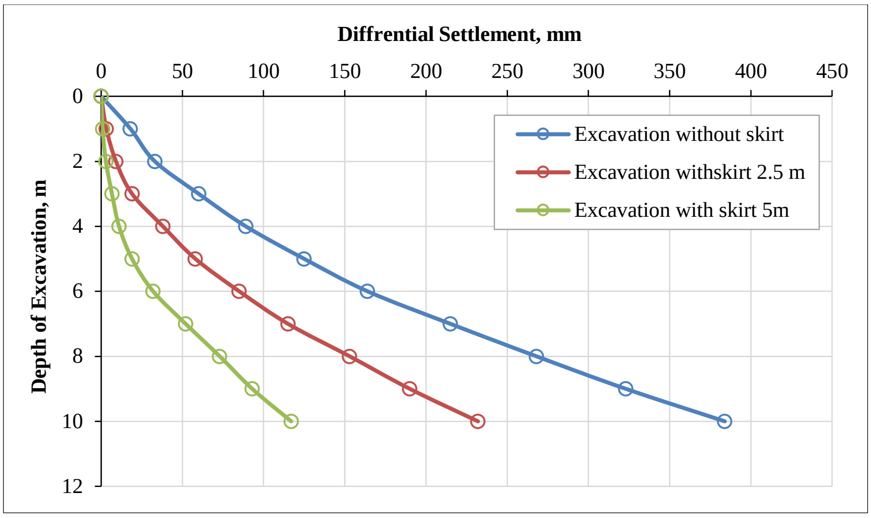


Figure 13. The change in differential settlement with increasing excavation depth for Case 2

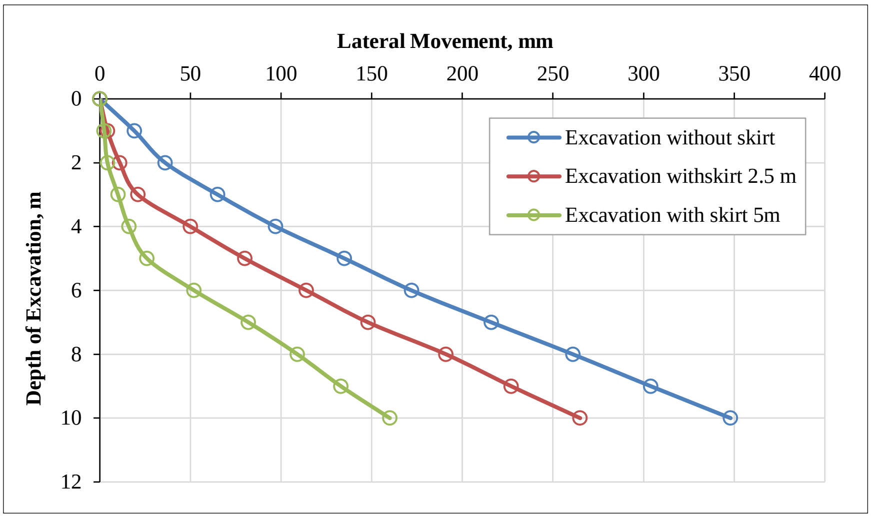


Figure 14. The change in lateral displacement with increasing excavation depth for Case 2

Differential settlement and lateral movement improved at depths of 2, 5, and 10 m when a skirt foundation with a depth of 0.25B (2.5 m) was used, with improvement percentages of 72%, 54%, and 40% for differential settlement and 69%, 41%, and 24% for lateral movement, respectively. When using a skirt foundation with a depth of 0.5 B (5 m), the percentage of improvement increased to 91.85% and 70% for differential settlement and 88%, 81%, and 54% for lateral movement, respectively. The improvement percentages are shown in Figures 15 and 16. Figure 17 presents the contour values of settlement and lateral displacement for the foundation in the second case.

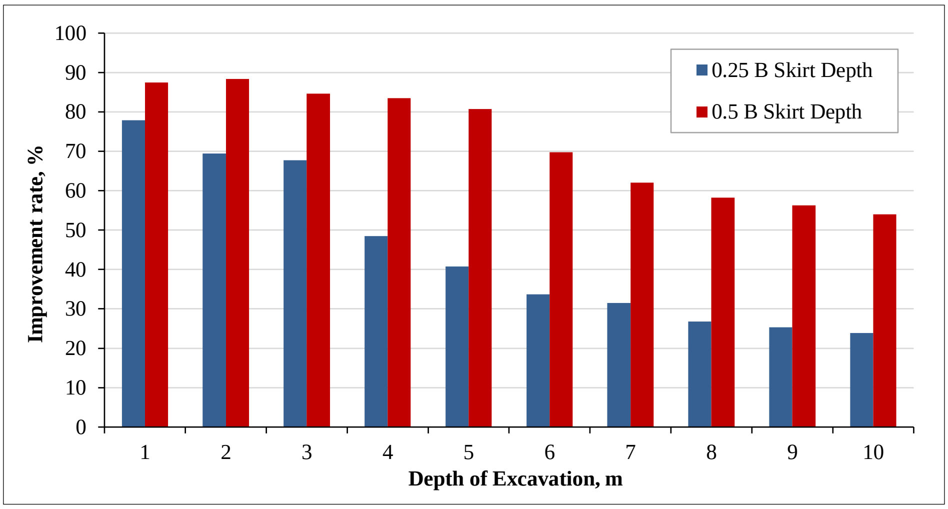


Figure 15. Percentage of differential settlement improvement after adding the skirt foundation for Case 2

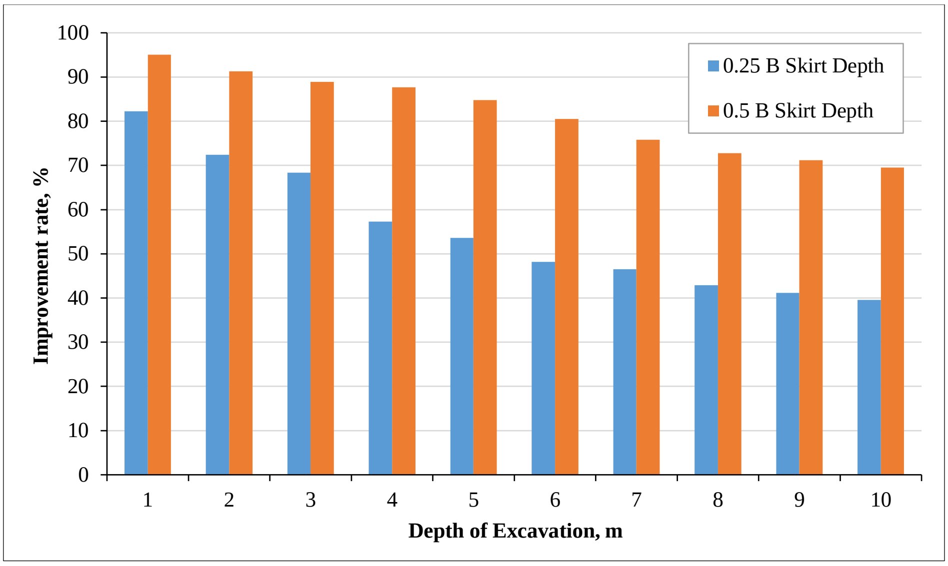
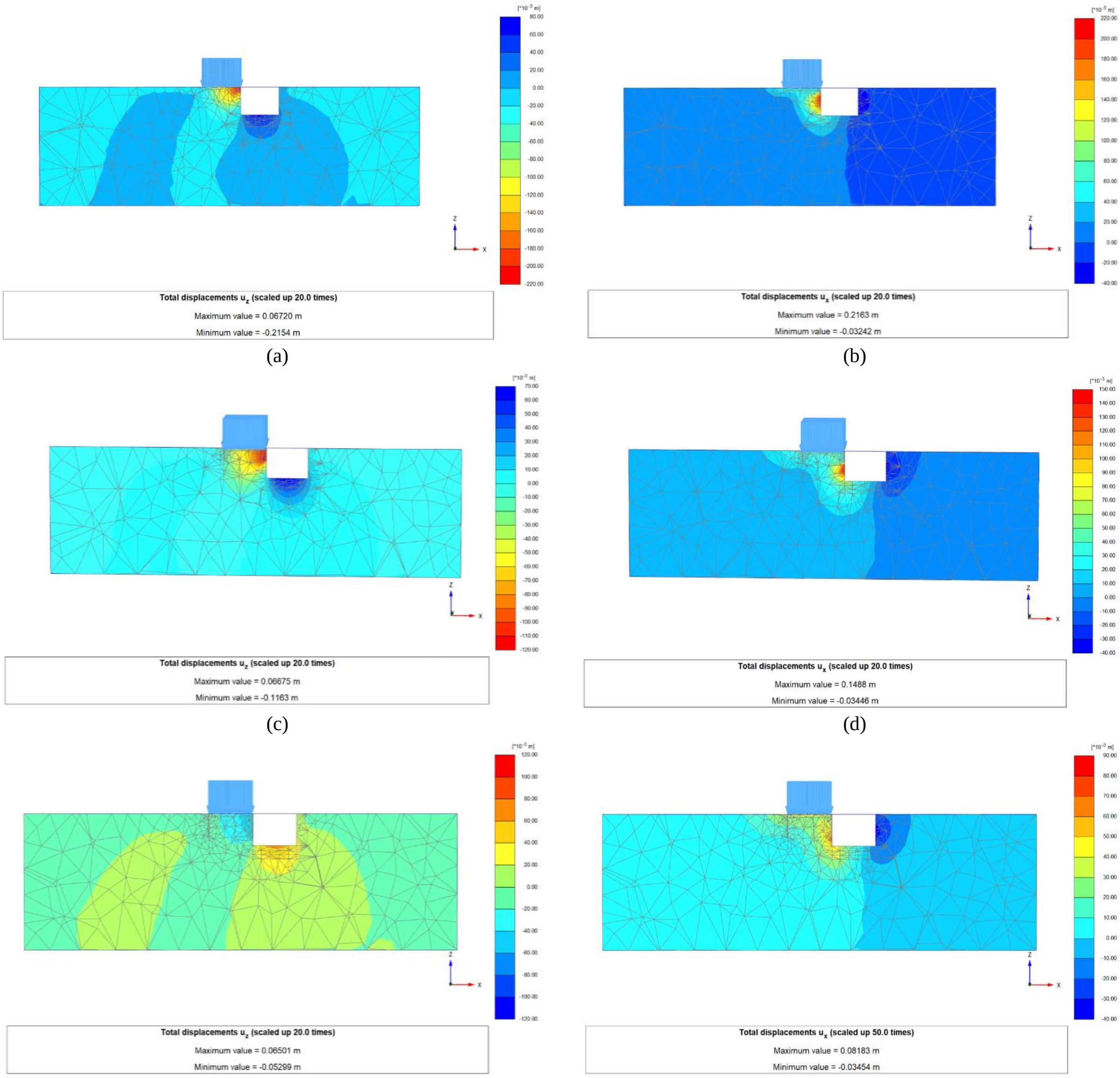


Figure 16. Percentage of lateral movement reduction after adding the skirt foundation for Case 2



(a) (b)

(c) (d)

(e) (f)

Figure 17. Section contours of Case 2 (a) differential settlement of raft without skirt (b) lateral displacement of raft without skirt (c) differential settlement of raft with skirt 0.25B (d) lateral displacement of raft with skirt 0.25B (e) differential settlement of raft with skirt 0.5B (f) lateral displacement of raft with skirt 0.5B.

6.2.2. Level of Damage Caused by Adjacent Excavations

Table 6 shows the levels of damage to the building for the second case, indicating that the level of damage increased to a high at a depth of 4m due to the higher load compared to Case 1. When a skirt foundation with a depth of 0.25B (2.5m) was used, the high damage level occurred at a depth of 6m, which was more than twice the depth of the skirt. Using a skirt with a depth of 0.5B (5m), the high damage level reached 9m, indicating that the building would be safer if the excavation depth did not exceed 5m.

Table 6. The degree of damage to the building under the effect of a load of 150 kPa (dimension of raft foundation 10×10 m)

Excavation Depth (m)	Without skirt			With skirt (0.25B)			With skirt (0.5B)		
	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level
1	18	0.0018	Light	3.2	0.00032	Negligible	0.89	0.000089	Negligible
2	33	0.0033	Light	9.1	0.00091	Negligible	2.88	0.000288	Negligible
3	60	0.006	Moderate	19	0.0019	light	6.64	0.000664	Negligible
4	89	0.0089	High	38	0.0038	Moderate	11	0.0011	Light
5	125	0.0125	High	58	0.0058	Moderate	19	0.0019	Light
6	164	0.0164	High	85	0.0085	High	32	0.0032	Moderate
7	215	0.0215	High	115	0.0115	High	52	0.0052	Moderate
8	268	0.0268	High	153	0.0153	High	73	0.0073	Moderate
9	323	0.0323	High	190	0.019	High	93	0.0093	High
10	384	0.0384	High	232	0.0232	High	117	0.0117	High

6.3. Case 3

In this third case, the dimensions of the raft foundation differed from those of the previous two cases, measuring 5×10 m under a load of 100 kPa. Three groups were considered: the first group used a raft foundation without a skirt, the second used a raft foundation with a skirt to a depth of 0.25B (1.25 m), and the third used a skirt to a depth of 0.5B (2.5 m). The effect of the graduated excavation ranging from 1 to 10 m and the results were as follows:

6.3.1. Variation of Differential Settlement and Rotation Angle with Addition of Skirt Foundation

The results of differential settlement and lateral movement with depth of excavation are shown in Figures 18 and 19. It is clear that using a skirt foundation increased the stability of the building, and this stability further improved as the depth of the skirt foundation increased. The use of a skirt with a depth of 0.25B (1.25 m) reduced differential settlement and lateral movement at depths of 2, 5, and 10 m by rates of 62%, 36%, and 26% for differential settlement and 32%, 17%, and 11% for lateral movement, respectively. Using a skirt with a depth of 2.5B (2.5 m) improved the building's safety, and the degree of reduction in differential settlement and lateral movement at depths of 2, 5, and 10 m were 83%, 61%, and 44% for differential settlement and 49%, 38%, and 16% for lateral movement, respectively, as clearly shown in Figures 20 and 21. Figure 22 illustrates the contour values of settlement and lateral displacement for the foundation in Case 3. The contour values are shown at a depth of 5 m to demonstrate the behavior of the skirt foundation at a depth exceeding its maximum depth of 2.5 m.

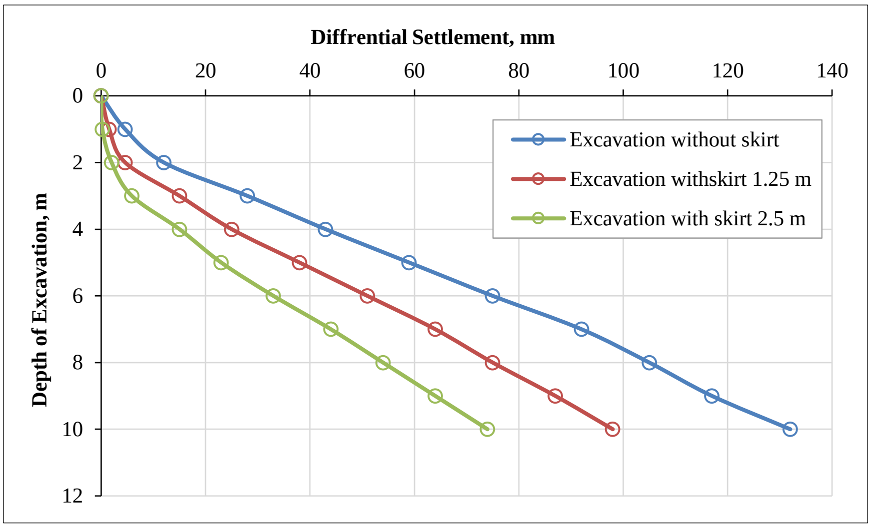


Figure 18. The change in differential settlement with increasing excavation depth for Case 3

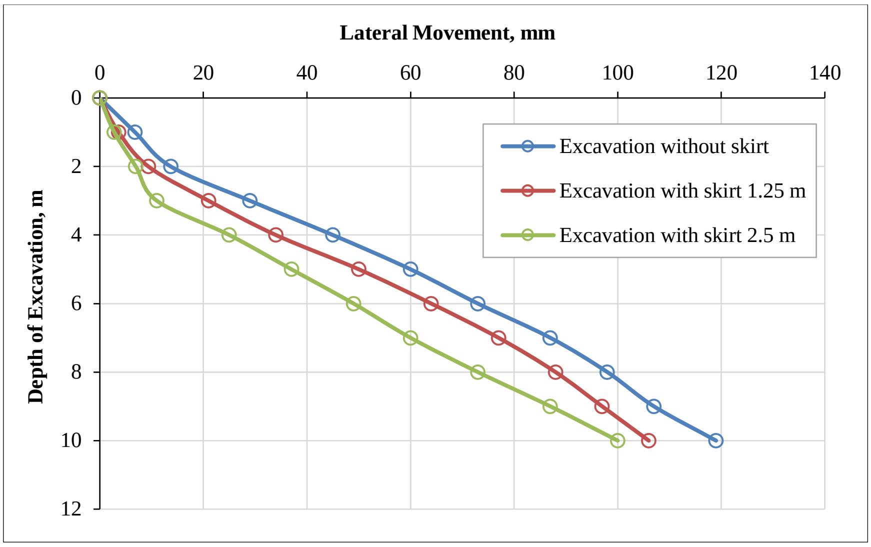


Figure 19. The change in lateral displacement with increasing excavation depth for Case 3

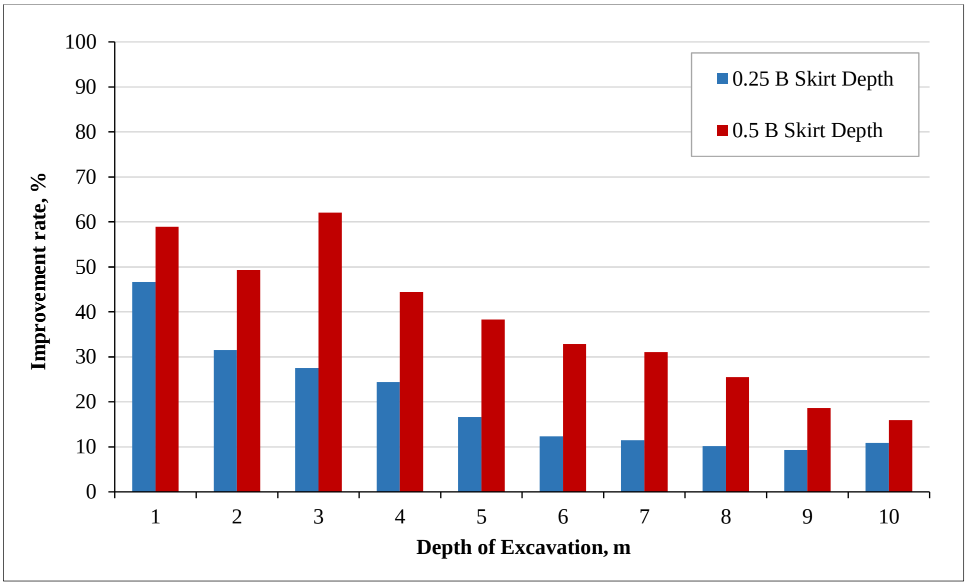


Figure 20. Percentage of differential settlement improvement after adding the skirt foundation for Case 3

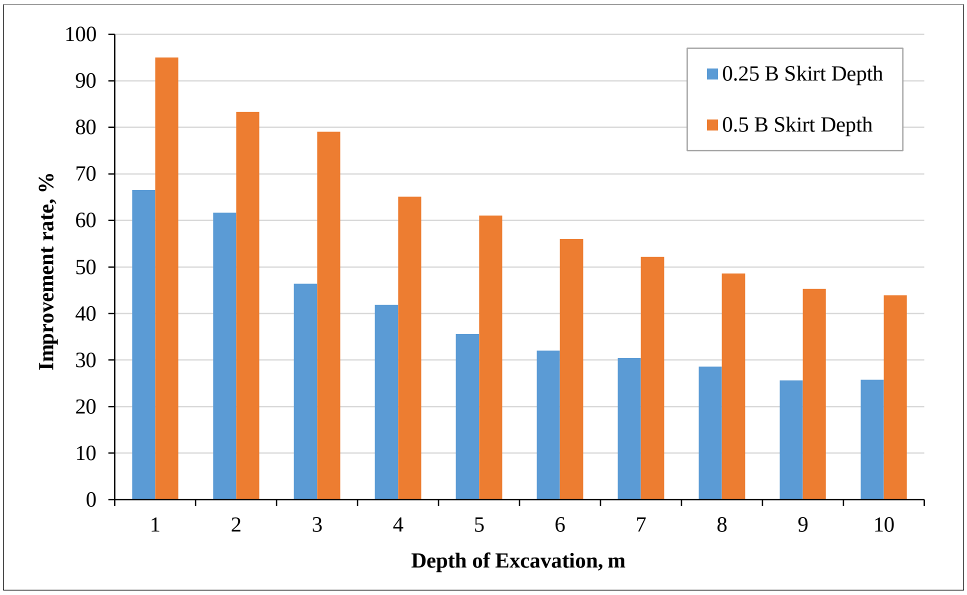
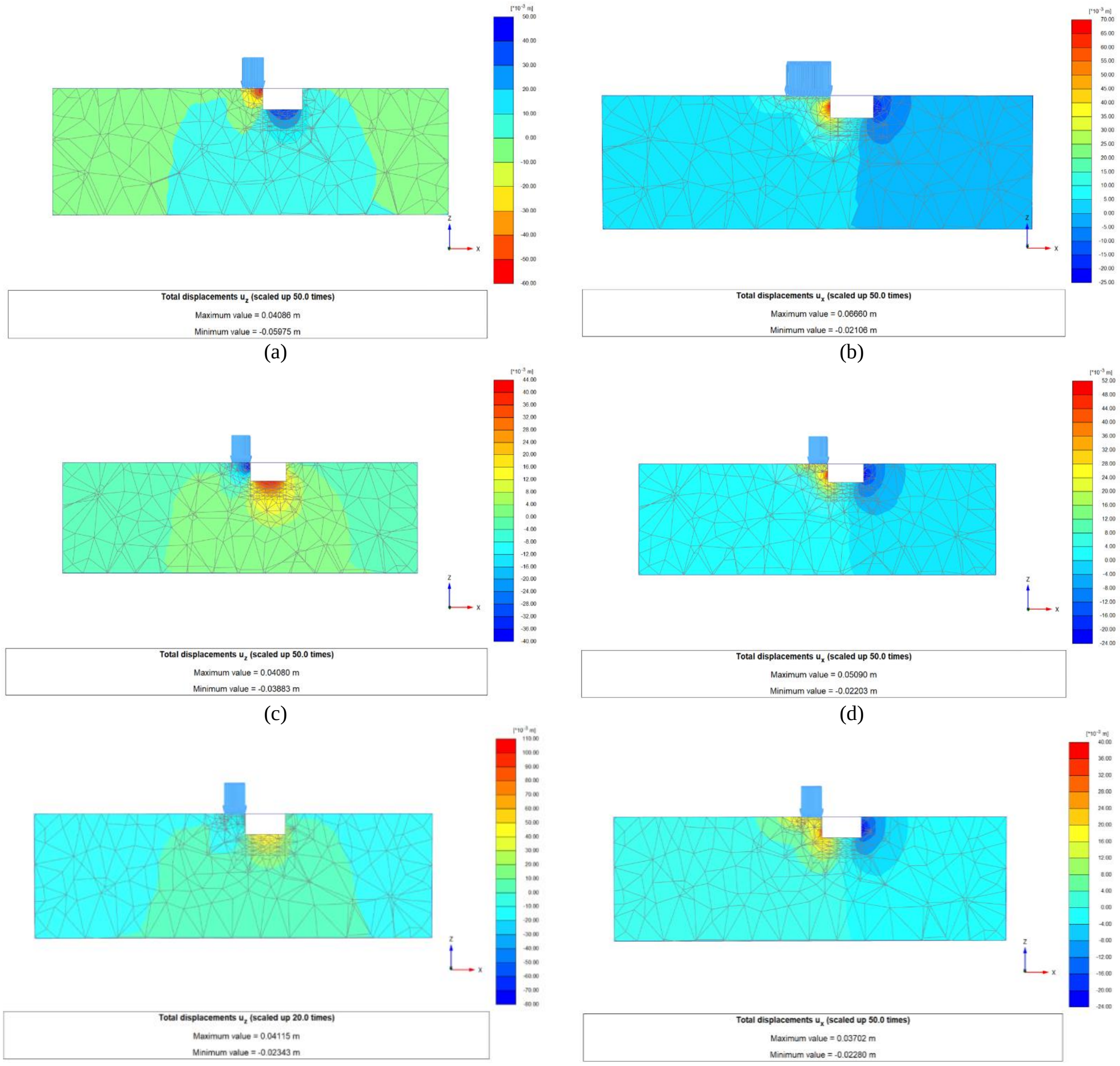


Figure 21. Percentage of lateral movement reduction after adding the skirt foundation for Case 3



(a) (b)

(c) (d)

(e) (f)

Figure 22. Section contours of Case 3 (a) differential settlement of raft without skirt (b) lateral displacement of raft without skirt (c) differential settlement of raft with skirt 0.25B (d) lateral displacement of raft with skirt 0.25B (e) differential settlement of raft with skirt 0.5B (f) lateral displacement of raft with skirt 0.5B.

6.3.2. Level of Damage Caused by Adjacent Excavations

In Table 7, similar to Case 1, the high-level damage occurred at 7 m, but the level of moderate was observed at 3 m, compared to 3 m in Case 1. Using a skirt with a depth of 0.25B (1.25 m) raised the safe level to 4 m, and using the skirt with a depth of 0.5B (2.5 m) extended the safe level to 5 m, which was double the skirt depth. The rectangular dimensions of the raft foundation, rather than the square dimensions in some cases, introduced a rotation factor that affected the determination of damage level.

Table 7. The degree of damage to the building under the effect of a load of 100 kPa (dimension of raft foundation 5×10 m)

Excavation Depth(m)	Without skirt			With skirt (0.25B)			With skirt (0.5B)		
	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level
1	4.6	0.00092	Negligible	1.54	0.000308	Negligible	0.23	0.000046	Negligible
2	12	0.0024	Light	4.6	0.00092	Negligible	2	0.0004	Negligible
3	28	0.0056	Moderate	15	0.003	Light	5.87	0.001174	Negligible
4	43	0.0086	Moderate	25	0.005	Light	15	0.003	Light
5	59	0.0118	Moderate	38	0.0076	Moderate	23	0.0046	Light
6	75	0.015	Moderate	51	0.0102	Moderate	33	0.0066	Moderate
7	92	0.0184	High	64	0.0128	Moderate	44	0.0088	Moderate
8	105	0.021	High	75	0.015	Moderate	54	0.0108	Moderate
9	117	0.0234	High	87	0.0174	High	64	0.0128	Moderate
10	132	0.0264	High	98	0.0196	High	74	0.0148	Moderate

6.4. Case 4

The fourth case was similar to the third case in terms of the dimensions of the raft foundation (5×10 m), but it had a higher load effect of 150 kPa. Similarly, three groups were chosen: one without using the skirt foundation and two with using the skirt foundation at depths of 0.25B (1.25 m) and 0.5B (0.25 m). The results were as follows:

6.4.1. Variation of Differential Settlement and Rotation Angle with Addition of Skirt Foundation

As in Case 2, the differential settlement and lateral movement increased because of the higher effective load, as shown in Figures 23 and 24. The differential settlement and lateral movement decreased when a skirt foundation was used, with the rate of decrease depending on the depth of the skirt as shown in Figures 25 and 26. The rate of decrease in differential settlement and lateral movement at depths of 2, 5, and 10 m was 62%, 44%, and 33% and 50%, 30%, and 20%, respectively, for a skirt foundation with a depth of 0.25 B (1.25 m). For a skirt foundation with a depth of 0.5B (2.5 m), the rates were 78%, 69%, 54%, and 64%, 57%, and 40%, respectively. Figure 27 shows the contour values of the settlement and lateral displacement of the foundation in case 4.

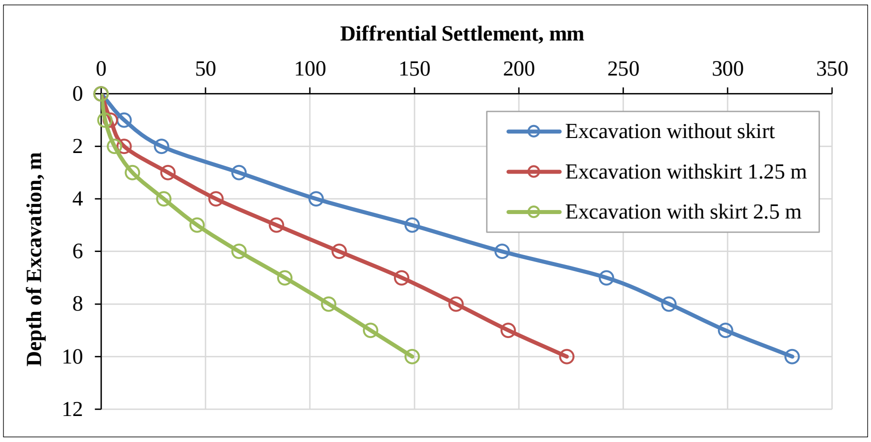


Figure 23. The change in differential settlement with increasing excavation depth for Case 4

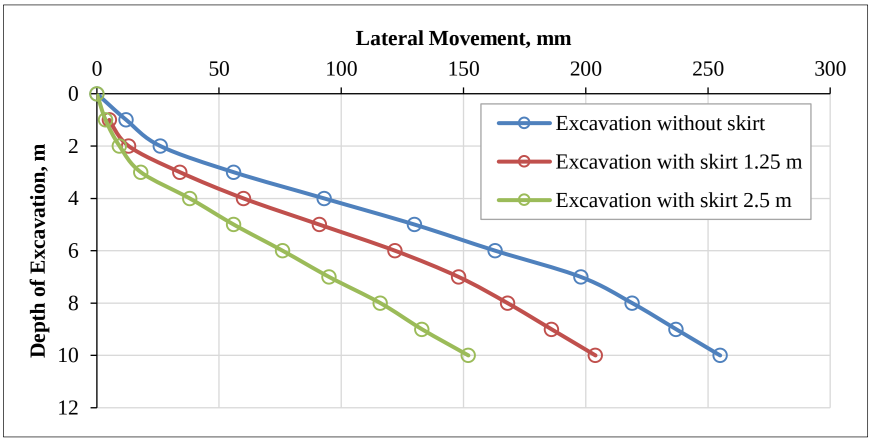


Figure 24. The change in lateral displacement with increasing excavation depth for Case 4

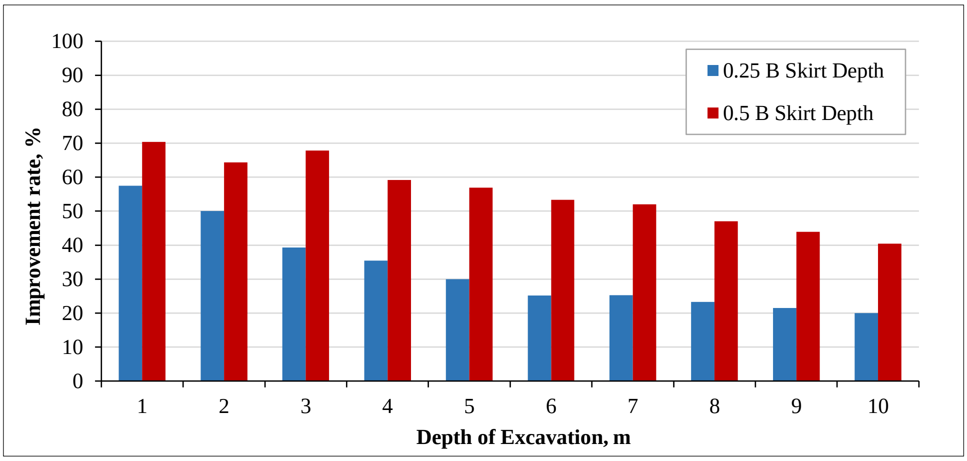


Figure 25. Percentage of differential settlement improvement after adding the skirt foundation for Case 4

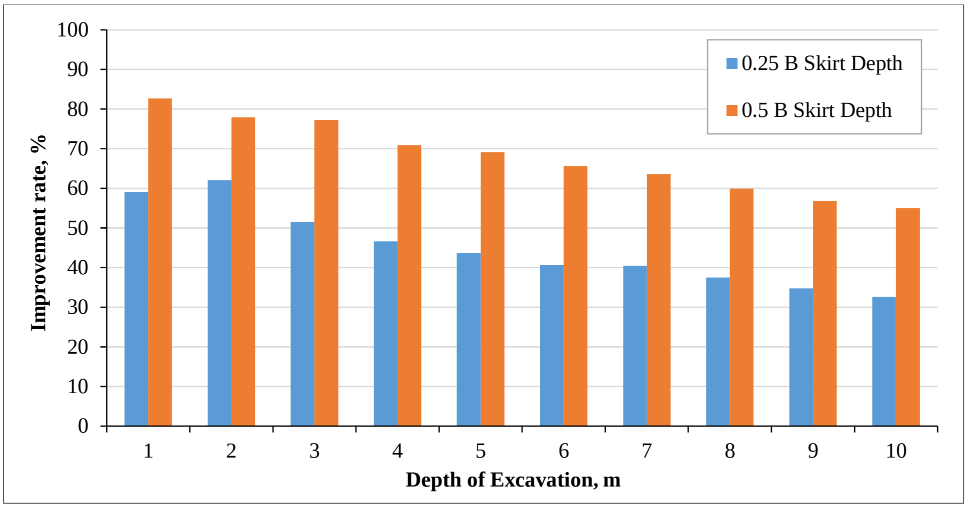


Figure 26. Percentage of lateral movement reduction after adding the skirt foundation for Case 4

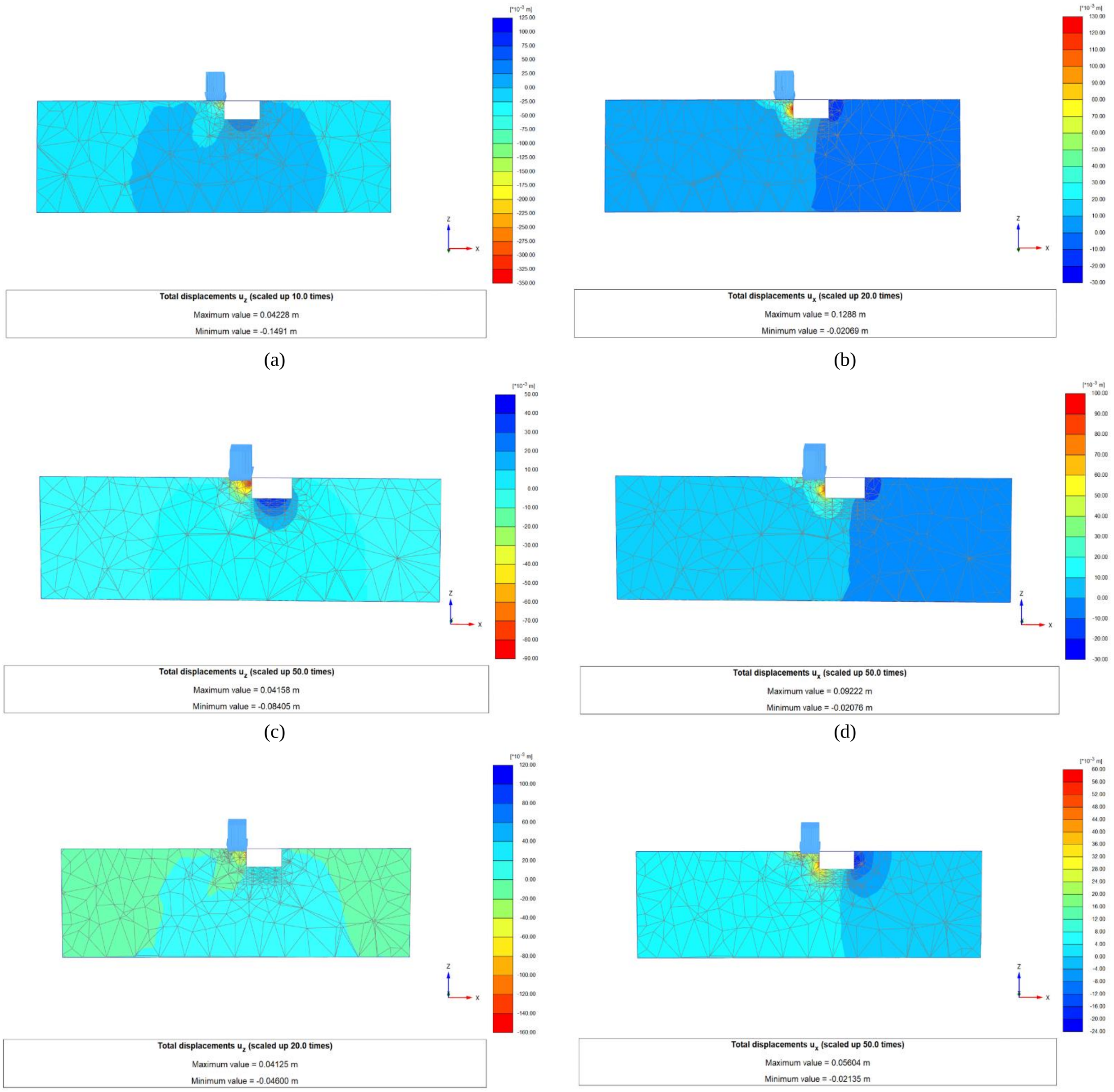


Figure 27. section contours of case 4 (a) differential settlement of raft without skirt (b) lateral displacement of raft without skirt (c) differential settlement of raft with skirt 0.25 B (d) lateral displacement of raft with skirt 0.25 B (e) differential settlement of raft with skirt 0.5 B (f) lateral displacement of raft with skirt 0.5 B.

6.4.2. Level of Damage Caused by Adjacent Excavations

The most important factor in evaluating the importance of using a skirt foundation was assessing the extent of damage resulting from adjacent excavations and determining the acceptable depth of excavations adjacent to the building without causing damage. As shown in Table 8, using a skirt foundation with a depth of 0.25B (1.25 m) established a safe level at an excavation depth of 2 m. While using a skirt foundation with a depth of 0.5B (2.5 m) increased the safe level to 3 m. This indicated that the increasing depth of the skirt led to a greater safe level to excavate adjacent to the building.

Table 8. The degree of damage to the building under the effect of a load of 150 kPa (dimension of raft foundation 5×10 m)

Excavation Depth(m)	Without skirt			With skirt (0.25B)			With skirt (0.5B)		
	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level	$\Delta\delta_V$ (mm)	(θ_{max})	Impact level
1	11	0.0022	Light	4.5	0.0009	Negligible	1.9	0.00038	Negligible
2	29	0.0058	Moderate	11	0.0022	Light	6.4	0.00128	Negligible
3	66	0.0132	Moderate	32	0.0064	Moderate	15	0.003	Light
4	103	0.0206	High	55	0.011	Moderate	30	0.006	Moderate
5	149	0.0298	High	84	0.0168	High	46	0.0092	Moderate
6	192	0.0384	High	114	0.0228	High	66	0.0132	Moderate
7	242	0.0484	High	144	0.0288	High	88	0.0176	High
8	272	0.0544	High	170	0.034	High	109	0.0218	High
9	299	0.0598	High	195	0.039	High	129	0.0258	High
10	331	0.0662	High	223	0.0446	High	149	0.0298	High

7. Conclusions

This research aims to develop solutions to the problems and damages that buildings may experience due to adjacent excavations. To achieve this, a raft foundation was selected in two forms with dimensions of 10×10 m and 5×10 m, subjected to vertical loads of 100 or 150 kPa. Excavations were carried out adjacent to the foundation incrementally, starting at a depth of 1 m and increasing progressively by 1 m until reaching a maximum depth of 10 m. The study compared the cases without a skirt foundation to those incorporating a skirt foundation at depths of 0.25B and 0.5B. The objective was to assess the effect of adding a skirt foundation and its depth on the overall stability of the building. The following conclusions were reached:

- Surrounding the soil under the raft foundation with a skirt played a role in minimizing damage to the building by reducing differential settlement and lateral movement.
- The dimensions of the foundation were crucial in resisting the lateral movement of the soil caused by excavations, as well as in reducing the angle of rotation. The results indicated that the foundation dimensions of 10×10 m were more susceptible to differential settlement than the foundation of 10×5 m because the excavations were adjacent to the smaller width of the foundation.
- From the results obtained, the selection of the skirt depth depends on two important parts: the dimensions of the foundation and the building load stress. Since the transferred stresses were high at 150 kPa, the foundation at a depth of 0.5 B was more effective in reducing differential settlement and lateral movement of the soil than a depth of 0.25 B.
- All tables that analyzed the results of the damage level showed a decrease in the effect of differential settlement and the angle of rotation when the foundation was surrounded by a skirt. In the worst-case scenario, where the foundation dimensions were 5×10 m and the building load was 150 kPa. It was noted that the differential settlement decreased to about half of what it was without a skirt. The improvement rate was notably significant at the depths where excavations were adjacent to the skirt wall; however, the improvement percentage gradually decreased as the soil moved further away from the skirt wall at greater depths.
- Excavation adjacent to the building should not exceed 0.25B for unsupported conditions. In the skirt-raft foundation system, the excavation depth beneath the skirt foundation should also be limited to 0.25B to ensure stability.

8. Declarations

8.1. Author Contributions

Conceptualization, B.A.A. and H.M.S.; methodology, B.A.A. and H.M.S.; software, H.M.S.; validation, H.M.S.; formal analysis, B.A.A. and H.M.S.; investigation, H.M.S.; writing—original draft preparation, B.A.A., H.M.S., and M.M.J.; writing—review and editing, A.A.; visualization, B.A.A. and H.M.S.; supervision, B.A.A.; project administration, B.A.A. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available on request from the corresponding author.

8.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

8.4. Conflicts of Interest

The authors declare no conflict of interest.

9. References

[1] Dmochowski, G., & Szolomicki, J. (2021). Technical and structural problems related to the interaction between a deep excavation and adjacent existing buildings. Applied Sciences (Switzerland), 11(2), 1–19. doi:10.3390/app11020481.

[2] Dong, J., Bai, Q., Zhao, W., & Wang, B. (2023). Test Study on the Influence of Foundation Pit Excavation on the Surface Settlement of Sandy Soil Natural Foundation of Adjacent Buildings. Buildings, 13(5), 1293. doi:10.3390/buildings13051293.

[3] Zhang, D. (2023). Influences of Deep Foundation Pit Excavation on the Stability of Adjacent Ancient Buildings. Buildings, 13(8), 4. doi:10.3390/buildings13082004.

[4] Mangi, N., Kumar, M., Mangnejo, D. A., Karira, H., Jhatial, A. A., & Lakhair, F. R. (2019). Crack Pattern Investigation in the Structural Members of a Framed Two-Floor Building due to Excavation-Induced Ground Movement. Engineering, Technology and Applied Science Research, 9(4), 4463–4468. doi:10.48084/etasr.2923.

[5] Schuster, M., Kung, G. T.-C., Juang, C. H., & Hashash, Y. M. A. (2009). Simplified Model for Evaluating Damage Potential of Buildings Adjacent to a Braced Excavation. Journal of Geotechnical and Geoenvironmental Engineering, 135(12), 1823–1835. doi:10.1061/(asce)gt.1943-5606.0000161.

[6] Piciullo, L., Ritter, S., Lysdahl, A. O. K., Langford, J., & Nadim, F. (2021). Assessment of building damage due to excavation-induced displacements: The GIBV method. Tunnelling and Underground Space Technology, 108. doi:10.1016/j.tust.2020.103673.

[7] Khalid, M. H., & Alshameri, B. (2022). Determination of safe depth and lateral distance of unsupported excavation near mat foundation in cohesive soils using Plaxis. Journal of Applied Science and Engineering, 25(2), 249–260. doi:10.6180/jase.202204_25(2).0011.

[8] Castaldo, P., Calvello, M., & Palazzo, B. (2013). Probabilistic analysis of excavation-induced damages to existing structures. Computers and Geotechnics, 53, 17–30. doi:10.1016/j.compgeo.2013.04.008.

[9] Zhao, J., Ritter, S., & DeJong, M. J. (2022). Early-stage assessment of structural damage caused by braced excavations: Uncertainty quantification and a probabilistic analysis approach. Tunnelling and Underground Space Technology, 125. doi:10.1016/j.tust.2022.104499.

[10] Zhang, X., & Zhan, Z. (2021). Evaluation of Risk of Building Damage due to Deep Excavations via Numerical Modelling. Advances in Civil Engineering, 2021. doi:10.1155/2021/6646094.

[11] Bjerrum, L. (1963). Discussion on compressibility of soils. Proceedings of the European conference on soil mechanics and foundation engineering, 24-27 September, 1963, Budapest, Hungary.

[12] Yang, Y., Li, X., & Chen, Y. (2022). The Influence of Different Excavation Methods on Deep Foundation Pit and Surrounding Environment. Lecture Notes in Civil Engineering, 213 LNCE, 109–129. doi:10.1007/978-981-19-1260-3_11.

[13] Zhang, Q. (2020). Deformation analysis of deep foundation pit excavation in China under time-space effect. Geotechnical Research, 7(3), 146–152. doi:10.1680/jgere.20.00009.

[14] Burland, J. B., & Wroth, C. P. (1975). Settlement of buildings and associated damage. Proceedings of the Conference of the British Geotechnical Society, No. CP 33/75.

[15] Wang, Z. Yu, Gu, D. Ming, & Zhang, W. Gang. (2020). Influence of excavation schemes on slope stability: A DEM study. Journal of Mountain Science, 17(6), 1509–1522. doi:10.1007/s11629-019-5605-6.

[16] Hu, J., & Ma, F. (2018). Failure Investigation at a Collapsed Deep Open Cut Slope Excavation in Soft Clay. Geotechnical and Geological Engineering, 36(1), 665–683. doi:10.1007/s10706-017-0337-2.

[17] Rankin, W. J. (1988). Ground movements resulting from urban tunnelling: Predictions and effects. Geological Society Engineering Geology Special Publication, 5(5), 79–92. doi:10.1144/GSL.ENG.1988.005.01.06.

[18] Shaaban, M. G., Kenawi, M. A., Senoon, A. A. A., & El-Naiem, M. A. A. (2023). Effects of excavation and construction sequence on behavior of existing pile groups. Innovative Infrastructure Solutions, 8(8), 223. doi:10.1007/s41062-023-01193-8.

[19] Al-Jorany, A. N., & Al-Qaisee, G. S. (2016). Field Observation of Soil Displacements Resulting Due Unsupported Excavation and Its Effects on Proposed Adjacent Piles. Journal of Engineering, 22(5), 11–28. doi:10.31026/j.eng.2016.05.02.

[20] Al-Soudani, W. H., & Albusoda, B. S. (2024). Experimental and numerical simulation of a ring and wings-open-ended pipe pile. Innovative Infrastructure Solutions, 9(1), 27. doi:10.1007/s41062-023-01323-2.

[21] Miao, Y., Liu, B., Liu, C., Shu, Z., & Wu, H. (2020). Experimental Study on Stability Analysis of a Structure during Excavation beneath This Structure. Advances in Civil Engineering, 2020(1), 9268927. doi:10.1155/2020/9268927.

[22] Wei, H. (2021). Influence of Foundation Pit Excavation and Precipitation on Settlement of Surrounding Buildings. Advances in Civil Engineering, 6638868. doi:10.1155/2021/6638868.

[23] Wang, K., Yang, Z., Guo, J., Dang, Y., & Yan, Y. (2023). Numerical Analysis of the Influence of Deep Excavation on Nearby Pile Foundation Building. Buildings, 13(11), 2842. doi:10.3390/buildings13112842.

[24] Soomro, M. A., Memon, K. F., Soomro, M. A., Memon, A., & Keerio, M. A. (2018). Single Pile Settlement and Load Transfer Mechanism due to Excavation in Silty Clay. Engineering, Technology & Applied Science Research, 8(1), 2485–2492. doi:10.48084/etasr.1666.

[25] Soomro, M. A., Brohi, A. S., Soomro, M. A., Bangwar, D. K., & Bhatti, S. A. (2018). 3D Numerical Modeling of Pile Group Responses to Excavation-Induced Stress Release in Silty Clay. Engineering, Technology & Applied Science Research, 8(1), 2577–2584. doi:10.48084/etasr.1748.

[26] Mangnejo, D. A., Soomro, M. A., Mangi, N., Halepoto, I. A., & Dahri, I. A. (2018). A Parametric Study of Effect on Single Pile Integrity Due to an Adjacent Excavation Induced Stress Release in Soft Clay. Engineering, Technology & Applied Science Research, 8(4), 3189–3193. doi:10.48084/etasr.2105.

[27] Yu, Z. T., Wang, H. Y., Wang, W., Ling, D. S., Zhang, X. D., Wang, C., & Qu, Y. H. (2021). Experimental and Numerical Investigation on the Effects of Foundation Pit Excavation on Adjacent Tunnels in Soft Soil. Mathematical Problems in Engineering, 5587857. doi:10.1155/2021/5587857.

[28] Liu, F., Zhang, X., Xiang, M., Lyu, J., Feng, R., & LIU, S. (2024). Experimental study on stress and deformation characteristics of foundation pit considering excavation width using 3D printing technology. Frontiers in Earth Science, 12. doi:10.3389/feart.2024.1373140.

[29] Xie, L., & Liu, S. (2022). Analysis of the influence of super large area and super deep foundation pit excavation construction on surrounding subways. Journal of Mechatronics and Artificial Intelligence in Engineering, 3(2), 65–75. doi:10.21595/jmai.2022.22776.

[30] Uba Uge, B., & Guo, Y. (2020). Deep Foundation Pit Excavations Adjacent to Disconnected Piled Rafts: A Review on Risk Control Practice. Open Journal of Civil Engineering, 10(03), 270–300. doi:10.4236/ojce.2020.103023.

[31] Al-Qaisee, G. S., Ahmed, M. D., & Ahmed, B. A. (2020). Performance of piled raft foundations under the effect of dewatering nearby an open pit. IOP Conference Series: Materials Science and Engineering, 737(1), 12081. doi:10.1088/1757-899X/737/1/012081.

[32] Liang, Y. Y., Liu, N. W., Yu, F., Gong, X. N., & Chen, Y. T. (2019). Prediction of response of existing building piles to adjacent deep excavation in soft clay. Advances in Civil Engineering, 8914708. doi:10.1155/2019/8914708.

[33] Niu, Y., Wang, Q., & Ma, F. (2023). Study on the Influence of Foundation Pit Excavation on the Deformation of Adjacent Subway Tunnel in the Affected Area of Fault Zones. Sustainability (Switzerland), 15(12), 9462. doi:10.3390/su15129462.

[34] Amarasinghe, M. P., De Silva, L. I. N., & Gallage, C. (2018). The effect of lateral confinement on the settlement characteristics of shallow foundations on sand. GEOMATE Journal, 15(51), 258-265.

[35] Mohammadizadeh, M., Nadi, B., Hajiannia, A., & Mahmoudi, E. (2023). The undrained vertical bearing capacity of skirted foundations located on slopes using finite element limit analysis. Innovative Infrastructure Solutions, 8(4), 121. doi:10.1007/s41062-023-01070-4.

[36] Patel, S. K., & Singh, B. (2019). A parametric study on the vertical pullout capacity of suction caisson foundation in cohesive soil. Innovative Infrastructure Solutions, 4, 1-11. doi:10.1007/s41062-018-0188-6.

[37] Fattah, M. Y., Shlash, K. T., & Mohammed, H. A. (2014). Bearing Capacity of Rectangular Footing on Sandy Soil Bounded by a Wall. Arabian Journal for Science and Engineering, 39(11), 7621–7633. doi:10.1007/s13369-014-1353-7.

[38] Abd-Alhameed, H. J., & Al-Busoda, B. S. (2023). Experimental Study on the Behavior of Square-Skirted Foundation Rested on Gypseous soil Under Inclined Load. Journal of Engineering, 29(3), 27–39. doi:10.31026/j.eng.2023.03.03.

[39] Ahmed, B. A., Saleh, H. M., Jameel, M. M., & Al-Taie, A. (2024). Increasing the Performance of Ring Foundation to Lateral Loads by using a Skirt Foundation. Engineering, Technology & Applied Science Research, 14(6), 17629–17635. doi:10.48084/etasr.8617.

[40] Nazeer, S., & Dutta, R. K. (2021). Bearing capacity of embedded and skirted e-shaped footing on layered sand. Journal of Achievements in Materials and Manufacturing Engineering, 108(1), 5–23. doi:10.5604/01.3001.0015.4795.