

STAGE ANALYSIS OF FOUNDATION SETTLEMENT IN RETAINED EXCAVATIONS USING PLAXIS 2D

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ABSTRACT: The relevance of the topic is due to the need to design and construct foundations in conditions of dense urban development and weak soils. The aim of this work is to study the features of pile foundation design, taking into account the stability of the excavation and the effect of phased loading on foundation settlement. The novelty of the research lies in the numerical modeling of phased construction using a wall in the ground, as well as the analysis of changes in the stress-strain state of the foundation, taking into account the stages of pile installation. Calculations performed in the Plaxis 2D software environment showed that when a five-story building is fully loaded, the foundation settlement does not exceed 1 cm, which is within the maximum permissible values according to the standards. The maximum horizontal displacement of the enclosing wall was 0.45 cm, which also indicates its stability at an excavation depth of up to 3 m and the presence of anchors. The results confirm the effectiveness of the combined system—walls in the ground, anchors, and pile foundations—when building on weak soils in confined conditions. The work is of practical value for the engineering and geotechnical justification of construction solutions in densely built-up areas.

Keywords: Plaxis, Load, Foundation Pit, Retaining Wall, Pile

1. INTRODUCTION

In today's conditions of intensive growth in urban density, there is a need to develop areas with geotechnically complex, weak, and heterogeneous soils. This places high demands on engineering solutions aimed at ensuring the stability and durability of buildings and structures. This problem is particularly relevant in regions with harsh climatic conditions, where weak soils are subject to freezing and seasonal deformation. In such conditions, pile foundations demonstrate high efficiency, transferring loads from structures to more stable and dense soil layers, which reduces the risk of significant settlement and structural damage [1-3].

Design and construction in such environments require not only reliable foundation solutions but also the integration of advanced support systems and monitoring techniques to mitigate soil deformation and ensure excavation safety. The coupling effects between adjacent building activities, such as renovation with unloading–reloading processes, and simultaneous foundation pit excavation have been shown to exert a considerable influence on both the mechanical response of support structures and the surrounding soil mass. Numerical simulations and model experiments indicate that the sequence of construction stages plays a decisive role in controlling settlement, lateral displacement, and overall stability. At the same time, recent research has demonstrated that innovative reinforcement methods, including gradient pile foundations and cement–soil wrapped

pile systems, can significantly enhance the bearing capacity of weak soils and reduce structural defects. Therefore, a comprehensive approach that combines staged construction analysis, soil–structure interaction modeling, and effective reinforcement strategies is essential for ensuring structural safety in densely developed urban areas[4–8].

Recent advances in geotechnical engineering highlight diverse approaches to addressing soil–structure interaction challenges in excavation and foundation projects. Innovative solutions, such as prestressed concrete wall piles (PC wall piles), have demonstrated improved performance in inland waterway bank protection, where prestressing reduces bending moments and enhances load-bearing capacity under dredging embankment conditions. Complementary studies on soil arching effects within deep foundation pits (DFPs) reveal their critical influence on excavation stability, showing that optimal pile spacing, approximately three times the pile diameter, maximizes soil retention and minimizes deformations. In coastal areas, investigations of asymmetric pit-in-pit excavations supported by diaphragm walls and uplift piles confirm that combined systems effectively reduce wall deflections, base soil rebound, and embedment ratios, providing practical design recommendations for pile dimensions and spacing. Collectively, these studies underscore the importance of integrating advanced numerical modeling, soil–structure interaction analyses, and innovative reinforcement systems to optimize excavation safety and structural

performance in varied geotechnical environments[9–15].

Recent studies have expanded the understanding of excavation performance under complex geotechnical conditions, particularly in coastal and residual soil environments. Combined pit-in-pit systems with diaphragm walls and uplift piles greatly reduce wall deflections and improve excavation stability. Further investigations into pit-in-pit excavations within aquifer–aquitard systems using finite element limit analysis (FELA) clarified the mechanisms of hydraulic uplift failures, verified safety factors with strength reduction finite element methods, and proposed MARS-based predictive equations to optimize design reliability. In addition, geotechnical evaluations of retaining structures following partial collapses highlighted the importance of identifying failure causes, verifying stability with numerical and limit equilibrium analyses, and implementing rehabilitation measures such as pile and anchor system improvements. Collectively, these studies provide valuable insights into the mechanics, risks, and mitigation strategies of excavation support systems in geotechnically challenging environments[16–22].

Design and construction in such conditions requires a comprehensive approach, including the phased installation of retaining structures to ensure the stability of excavations and minimize soil deformation. For a detailed analysis of the interaction between soil and building structures, modern numerical methods implemented in software packages such as Plaxis 2D are widely used [23–27].

Quantitative findings from recent studies further illustrate the magnitude of soil and structural responses under excavation and foundation loading. For instance, Wang et al. (2023) [9] reported maximum surface settlements of 7.2–15.4 mm and wall deflections up to 12 mm for pile–beam–arch metro stations in soft soils, while Pham et al. (2016) [22] documented lateral wall movements of 0.5–1.2 % of excavation depth in deep pits of Ho Chi Minh City. Similarly, Kim et al. (2019) [26] demonstrated that increasing excavation width led to a rise in surface settlement from 10 mm to 25 mm, with corresponding reductions in the factor of safety from 2.8 to 1.7 for unbraced walls. These data provide a quantitative framework for interpreting the present study’s results and highlight the necessity of numerical modeling to predict deformation within acceptable safety margins.

In addition, calculation methods and experimental studies of retaining walls remain the subject of active scientific research and vary widely depending on the specifics of the design conditions. Systematic analysis and comparison of these methods contributes to the optimization of design solutions and the improvement of the safety of construction projects [28–33].

2. RESEARCH SIGNIFICANCE

This paper presents a comprehensive numerical analysis of the settlement of a pile foundation under the influence of a multi-stage load of a five-story business center in Astana. Particular attention is paid to the role of a protective retaining wall installed in the excavation pit, which reflects the real engineering challenges when working on weak soils in dense urban areas. The results obtained contribute to a deeper understanding of the interaction between structures and soil, and also serve as a basis for the development of effective engineering solutions in similar geotechnical conditions [34].

3. MATERIALS AND METHODS

The settlement of the foundation is analyzed using the Plaxis 2D software, which allows the construction process to be divided into sequential stages. This enables detailed observation of the changes occurring in the soil at each phase.

In the presented study, the Mohr–Coulomb constitutive model was used to simulate soil behaviour. This choice was made because the Mohr–Coulomb model is one of the most widely used and proven models in engineering geotechnics, especially in the initial stages of analysis. It provides a reasonable balance between ease of implementation and sufficient accuracy in assessing the stress-strain state of soils. The mechanical and physical properties of the soil were obtained based on laboratory tests are presented in Table 1.

Table 1. Mechanical and physical properties of the soil

Properties	Soil Types			Unit of measurement
	Sandy Loam	Clay Loam	Clay Loam	
I_L	0.2	0.3	0.3	-
I_P	0.15	0.18	0.18	-
ρ_s	2.7	2.72	2.6	g/cm ³
ρ	1.99	2.01	2	g/cm ³
ρ_d	1.75	1.79	1.8	g/cm ³
γ_s	26.46	26.6	25.48	kN/m ³
γ	19.5	19.69	19.6	kN/m ³
γ_d	17.2	17.5	17.64	kN/m ³
e	0.54	0.52	0.52	-
S_r	0.66	0.64	0.64	-
c	16	57	54	kPa
ϕ	26	24	22	°
E	23	27	28	MPa
R	255	290	290	kPa

The load applied to the foundation is calculated, with the program performing a two-dimensional cross-sectional analysis. The foundation must be capable of supporting the combined load from all five floors, ensuring that the settlement does not exceed the permissible limits specified in relevant standards, such as the Kazakhstan Construction Norms and

Rules. A summary of the loads applied across all floors is presented in Table 2.

Table 2. Summary of loads from all floors [35]

Floor	Calculation of loads addition		Overall
	$N_{p,t}$	$N_{s,t}$	$N_{o,t}$
5	48.02	4.4	52.42
4	94.49	9.04	103.53
3	134.96	13.68	148.64
2	178.43	18.32	196.75
1	221.9	22.96	244.86
foundation	263.75	27.6	291.35
wall	6.5		300

The total load transmitted to the foundation from all floors amounts to 300 tons, which is then transferred to the foundation's grillage beam. The specifications of the retaining wall installed in the excavation are presented in Table 3, while the anchor parameters are detailed in Table 4. The characteristics of the piles are summarized in Table 5.

Table 3. Retaining Wall in the excavation pit

Indicators	Designation	Value	Unit of measurement
Type of use Standard precision	Material type EA	Elastic $1.2 \cdot 10^6$	$\kappa\text{N/m}$
Accuracy of measurement	EI	$1.2 \cdot 10^5$	$\kappa\text{Nm}^2/\text{m}$
Equivalent thickness	d	0.346	m
weight	w	8.3	$\kappa\text{N/m/m}$
Poisson's ratio	-	0.15	-

Table 4. Anchored support system for the retaining wall in the excavation pit

Indicators	Designation	Value	Unit of measurement
Type of use Standard precision	Material type EA	Elastic $2 \cdot 10^6$	κN
Anchor assembly	L_s	2,5	m
Maximum bearing capacity	$F_{\text{max,comp}}$	$1 \cdot 10^3$	κN
	$F_{\text{max,tens}}$	$1 \cdot 10^3$	κN

The selection of piles depends on the soil type. For half of the building, piles with a length of 9 meters are driven, while for the remaining half, 7-meter piles are used. This differentiation is due to the varying depths of the non-compressible soil layer. Driving the piles into the non-compressible stratum is a crucial design decision to prevent excessive settlement of the structure [36].

In the present model, the piles are considered to be floating (friction) piles. The primary mechanism of load transfer occurs through shaft resistance, i.e., friction developed along the interface between the pile surface and the surrounding soil. This approach is widely used in geotechnical modeling.

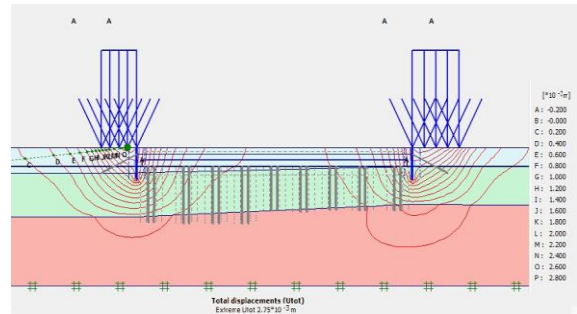
Table 5. Pile Specifications

Indicators	Designation	Value	Unit of measurement
Type of use Standard precision	Material type EA	Elastic $2.7 \cdot 10^6$	$\kappa\text{N/m}$
Accuracy of measurement	EI	20250	$\kappa\text{Nm}^2/\text{m}$
Equivalent thickness	d	0.3	m
weight	w	16	$\kappa\text{N/m/m}$
Poisson's ratio	-	0.2	-

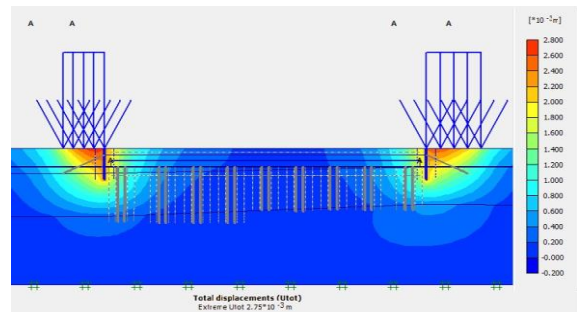
The workflow is divided into several stages:

In the first stage, the analysis area is defined and modeled in the Plaxis 2D software, with the soil stratification established according to geotechnical data. The average groundwater table is positioned at a depth of 3 meters, as determined from geodetic cross-sections. After defining the soil layers, a retaining wall is introduced around the perimeter of the planned excavation zone. This wall is constructed of cast-in-place reinforced concrete and is installed along all sides of the excavation area. Its primary function is to prevent soil collapse during excavation and ensure overall stability.

Additionally, surface loads from vehicular and pedestrian traffic are applied along the external side of the retaining wall to simulate realistic boundary conditions (Fig 1).



(a)



(b)

Fig.1 Settlement of the foundation in the isometric zone: (a) Settlement contours represented by isolines; (b) Settlement distribution visualized using color gradients

In the second stage, following the installation of the retaining wall, the excavation process begins. The soil is excavated to a depth of 1.5 meters, after which anchors are installed to ensure the stability of the retaining wall. Each anchor has a total length of 7 meters, with a cement-grouted section at the tip measuring 3 meters. The detailed specifications of the anchors are provided in Table 4 (Fig 2).

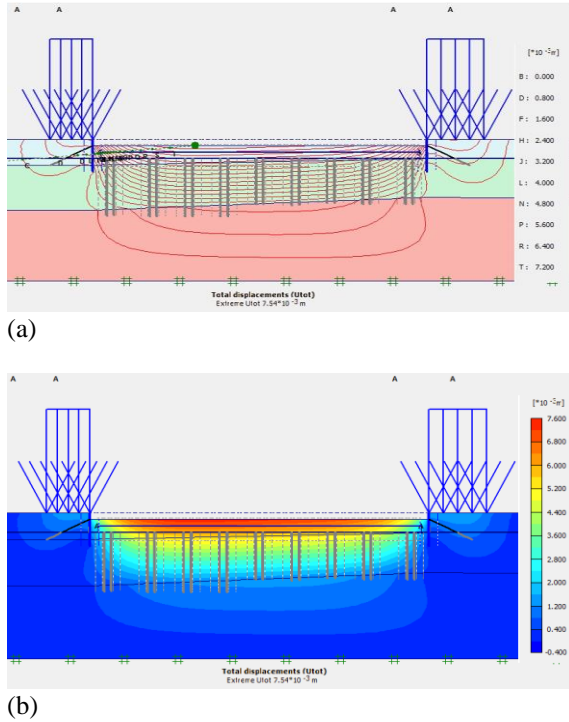


Fig.2 Settlement of the foundation in the isometric zone: (a) Settlement distribution represented by iso-lines; (b) Settlement distribution visualized by color shading

In the third stage, the excavation is carried out to its full design depth. The pit is carefully excavated to a depth of 3 meters, which precisely corresponds to the target design level specified in the project documentation. This stage is critical because achieving the correct excavation depth directly impacts the overall stability and safety of the structure. Upon reaching this depth, the installation of piles begins, which serve as the primary foundation elements to provide the necessary load-bearing capacity for the construction.

The detailed specifications of the piles, including their dimensions, materials, and installation methods, are provided in Table 5. A total of 18 piles are driven as part of the analysis. After pile installation, the pile heads are thoroughly cleaned of any soil or debris and are exposed at the required elevation to allow for accurate placement of reinforcement. This preparation ensures the proper connection between the piles and the reinforced concrete raft slab, which is subsequently installed on top of the piles (Fig 3).

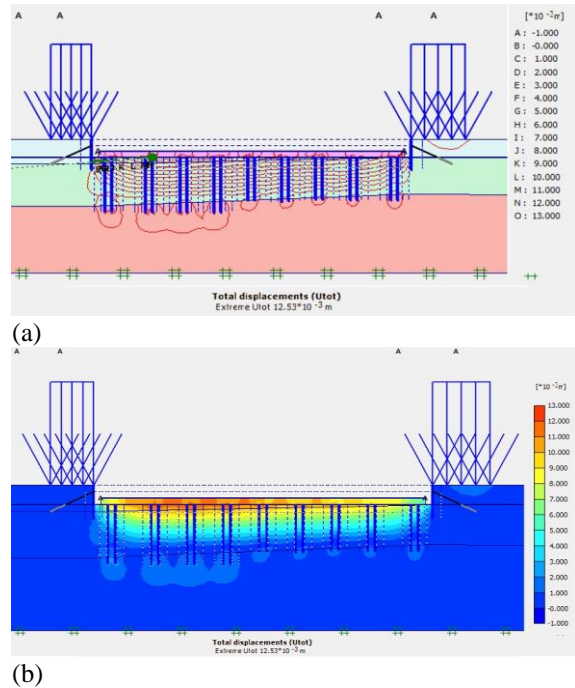


Fig.3 Settlement of the foundation in the isometric zone: (a) Settlement distribution represented by iso-lines; (b) Settlement distribution visualized by color shading

In the fourth stage, the load from the first three floors of the building is applied to the raft slab (Fig 4).

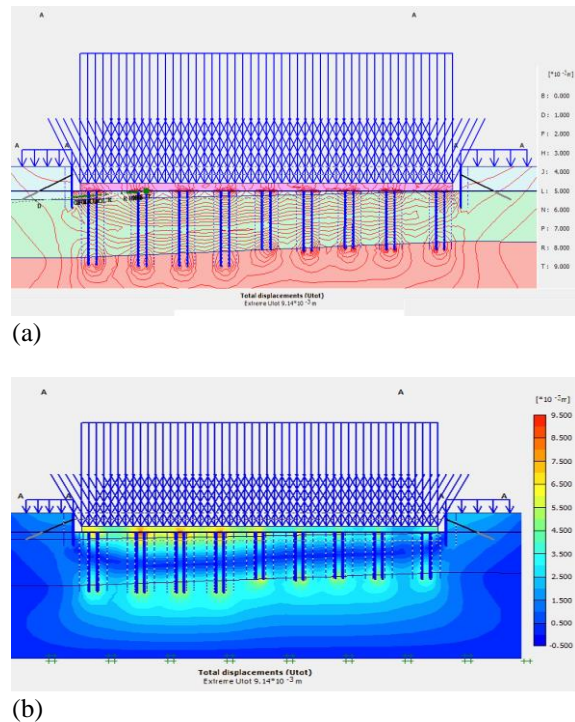


Fig.4 Settlement of the foundation in the isometric zone: (a) Settlement represented by iso-lines; (b) Settlement distribution visualized using color shading

In the fifth stage, the full design load from all five floors of the building is applied. The load distribution by floor is presented in Table 2. The total structural load amounts to 300 tons, which is uniformly distributed over the slab surface in accordance with the software's modeling parameters, expressed as an equivalent load per square meter (Fig 5).

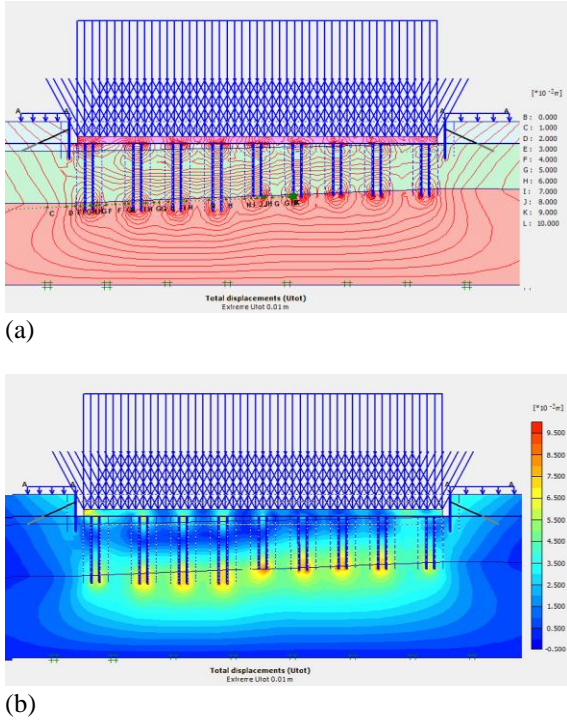


Fig.5 Foundation settlement in the isosurface zone (a) Settlement contours illustrated by isolines; (b) Settlement distribution depicted with color gradients

4. RESULTS AND DISCUSSION

The settlement behavior of the foundation soil under progressive construction loading was analyzed using Plaxis 2D, with results illustrated in Figures 1 through 5, corresponding to successive construction stages.

In the initial phase (Figure 1), the soil settlement is relatively uniform, with a maximum magnitude of approximately 0.275 cm. This stage reflects the undisturbed soil conditions before excavation activities.

During the second phase (Figure 2), the average settlement increases to 0.754 cm due to soil unloading and structural adjustments.

In the third phase (Figure 3), this phase exhibits a more pronounced settlement, with soil columns and the foundation slab displacing up to 1.253 cm.

The fourth phase (Figure 4) involves the resultant settlement at the slab's surface measures approximately 0.914 cm. This demonstrates the soil's consolidation response to incremental loading and

emphasizes the interaction between structural loads and subsoil behavior.

Finally, in the fifth phase (Figure 5), the settlement stabilizes at around 1 cm, indicating that the foundation-soil system reaches a new equilibrium state under maximum operational load conditions. The comparative analysis of Figures 4 and 5 elucidates the nonlinear settlement behavior under successive loading stages, under-scoring the necessity of staged construction modeling for accurate prediction of foundation performance (Fig 6).

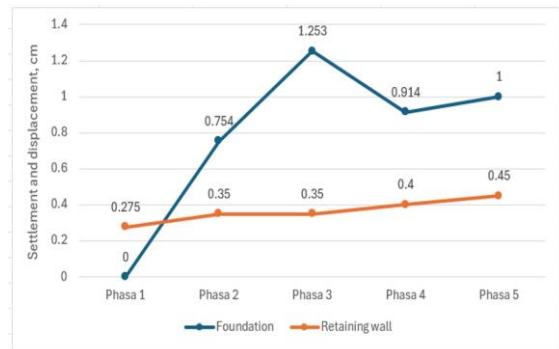


Fig.6 Settlement schedule for the foundation and stability of the retaining wall

The comprehensive modeling approach adopted in this study effectively captures the progressive soil-structure interaction and highlights the importance of anchoring systems in excavation stability. The results validate the efficiency of pile foundations in transferring structural loads to deeper, more competent soil layers, thereby mitigating excessive settlement. This research provides valuable insights for geotechnical engineers involved in urban construction projects on weak soils, supporting the design of safer and more reliable foundation systems under complex loading and excavation conditions [37].

Within the scope of this study, calculations were performed using a static, step-by-step model without taking time into account, which corresponds to the capabilities of the basic PLAXIS 2D functionality.

To verify the accuracy and reliability of the numerical modeling results obtained using Plaxis 2D, a comparative analysis was carried out with empirical settlement calculations based on the current Construction Norms and Rules of the Republic of Kazakhstan. Eq. (1)

$$S_i = \beta \sum_{i=1}^n \frac{\sigma_{zpi} \cdot h_i}{E_i} \quad (1)$$

where S_i is the foundation settlement, β is a dimensionless coefficient, σ_{zpi} is the average value of vertical normal stress (kPa), h_i is the thickness of the i -th soil layer (cm), E_i is the deformation modulus

of the i -th soil layer (kPa), n is the number of layers into which the compressible base layer is divided.

$$S_i = 0.013 \text{ m} = 1.3 \text{ cm}$$

The calculated settlement values from the finite element simulation were found to be in good agreement with those obtained using the standard empirical formulas, with deviations remaining within acceptable engineering limits. This correlation confirms the adequacy of the adopted soil parameters and modeling approach, and further validates the applicability of the staged construction method under the given geotechnical conditions.

A comparative assessment with recent studies further supports the validity of the present findings. Liu et al. (2023) observed maximum ground settlements of 2.5 mm (0.25‰ of excavation depth) in a 10 m-deep foundation pit, while Zhang et al. (2024) [5] reported horizontal displacements of 8.22–10.58 mm for excavation depths of 6–8 m, showing good agreement between field and numerical results. In more complex thermo-hydro-mechanical analyses, Hani and Evirgen (2024) [23] found ground settlements up to 1.7% of excavation depth and displacement ratios of 1.9–4.5%, illustrating the influence of wall material and thermal effects. Compared to these cases, the current study’s maximum settlement of 1 cm ($\approx 0.17\text{‰}$) lies at the lower bound of observed deformations, confirming the effectiveness of the adopted anchoring and pile systems. These results emphasize that staged construction modeling with soil–structure interaction provides reliable and conservative predictions of deformation, while also highlighting the importance of extending future work to three-dimensional analyses to capture spatial stress redistribution in pile groups.

To evaluate the robustness and reliability of the numerical model, a sensitivity analysis was performed on key geotechnical parameters that significantly influence soil-structure interaction and deformation behavior. The analysis focused on the following parameters: E , ϕ , c .

Each of the above parameters was independently varied by $\pm 20\%$ from its baseline value, while all other input parameters, boundary conditions, and model geometry remained constant. This parametric variation was conducted during the final simulation stage (Stage 5), corresponding to the fully loaded condition of the five-story structure. The numerical simulations were performed in Plaxis 2D using the Mohr–Coulomb soil model. The results are presented in Table 6.

The results indicate that:

A reduction in internal friction angle (ϕ) by 20% had the most significant effect on horizontal displacement, increasing wall deflection by 24%,

which highlights the sensitivity of lateral stability to shear strength parameters.

Deformation modulus (E) was the most influential factor for foundation settlement, where a 20% decrease in E resulted in a 15% increase in vertical displacement.

Table 6. Sensitivity analysis results

Parameter	Variation	Foundation Settlement (cm)	Wall Displacement (cm)	Deviation from Baseline (%)
Baseline	-	1.00	0.45	-
E-20%	-20%	1.15	0.50	+15%/+11%
E+20%	+20%	0.87	0.39	-13%/-13%
ϕ -20%	-20%	1.07	0.56	+7%/+24%
ϕ +20%	+20%	0.93	0.38	-7%/-16%
c-20%	-20%	1.06	0.51	+6%/+13%
c+20%	+20%	0.94	0.41	-6%/-9%

Cohesion (c) showed a moderate influence on both vertical and horizontal deformations, suggesting that while important, it is less critical than ϕ in terms of wall behavior.

The maximum deviation across all scenarios remained within 25% of the baseline values, indicating that the model exhibits stable and predictable behavior under moderate parameter uncertainty. This reinforces confidence in the selected soil parameters and validates the reliability of the staged construction modeling approach employed.

Despite the advantages of using Plaxis 2D for staged construction analysis and soil–structure interaction modeling, it is important to recognize the limitations associated with the two-dimensional plane strain assumption. For pile groups under multi-story buildings, three-dimensional (3D) effects such as load redistribution, edge pile behavior, and interaction between adjacent piles can have a significant influence on the stress–strain response of the foundation system. The 2D approach does not capture these spatial variations, which may lead to either conservative or non-conservative estimates of displacements and internal forces. In future studies, a comparative 3D analysis is recommended to validate the 2D results and better reflect the actual performance of pile foundations under complex loading and boundary conditions.

5. CONCLUSION

This study demonstrated the effectiveness of staged numerical modeling using Plaxis 2D for analyzing foundation settlement and retaining wall stability during the construction of a five-story business center in Astana on weak soils. The simulations showed that, under full building load, the maximum foundation settlement does not exceed 1 cm, which remains within the permissible limits defined by construction standards. Additionally, the maximum horizontal displacement of the retaining

wall was 0.45 cm, indicating sufficient wall stability at an excavation depth of up to 3 meters, supported by an anchored system.

A key contribution of this research is the use of a staged construction approach, which enabled a detailed analysis of stress–strain evolution in both soil and structural components throughout each phase—from retaining wall and anchor installation, through sequential excavation and pile driving, to progressive loading of the foundation slab. This methodology provides an accurate representation of soil–structure interaction and underscores the critical role of construction sequencing in maintaining structural stability and minimizing deformations.

The combined use of embedded retaining walls, ground anchors, and pile foundations has proven effective for construction on weak soils in densely developed urban environments, ensuring both safety and structural performance during and after construction.

Despite the high accuracy of the results, the study is subject to certain limitations due to the two-dimensional modeling framework, which does not capture three-dimensional effects such as edge conditions and pile group interactions. For enhanced precision, future work should include 3D numerical simulations, as well as field monitoring of comparable construction projects for validation.

Further research will consider dynamic loading conditions, seasonal groundwater level fluctuations, and the integration of advanced structural health monitoring technologies. These developments will contribute to improved reliability of design decisions and enhance the long-term safety of buildings constructed on soft ground in urban settings.

In conclusion, the presented methodology and quantitative findings offer valuable insights for geotechnical design and construction practices in challenging soil conditions. The results confirm that with a properly implemented staged construction sequence and a rational combination of engineering solutions, it is possible to effectively control deformations and ensure structural stability, even under complex geotechnical constraints.

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