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PERFORMANCE OF SHALLOW FOUNDATIONS ON WATER-SATURATED CLAY SOILS AND THEIR REINFORCEMENT USING MICROPILES: A CASE STUDY IN ASTANA

*Nurlybek Kushkarbayev[1], Denis Tsygulyov [1], Serik Yenkebayev [1], Jeong Ku Kang [2]and Assilkhan Abu[3]

[1]Department of Design of Buildings and Structures, Faculty of Architecture and Civil Engineering, L.N. Gumilyov Eurasian National University, Astana, Kazakhstan
[2] Dept. of Civil and Environmental Engr., Incheon National University, Senior researcher of Korea Consultant, Co., Ltd., Republic of Korea
[3]Institute of Architecture and Civil Engineering, Satbayev University, Kazakhstan

*Corresponding Author, Received: 29 April 2026, Revised: 07 June 2026, Accepted: 19 June 2026

ABSTRACT: The relevance of this topic stems from the need to ensure the reliable performance of shallow foundations in conditions of weak, water-saturated clay soils and high groundwater levels, which are characteristic of the northern regions of Kazakhstan. The objective of this study is to investigate the performance characteristics of shallow foundations and to evaluate the effectiveness of their reinforcement using micropiles in complex engineering-geological conditions. The scientific novelty of the study lies in a comprehensive approach that includes field surveys, analytical calculations using the BASE software package, and numerical modeling in the PLAXIS 2D environment for a real-world site, taking into account the interaction of the "subgrade–foundation" system under high groundwater levels. The calculations showed that the existing strip foundations are operating near the ultimate limit state in terms of deformation (K = 0.98), while a sufficient safety margin remains in terms of strength (K = 0.79). Numerical modeling showed that foundation deformations are primarily determined by the compressibility of the upper weak soil layer. The use of micropiles significantly reduces settlement and redistributes stresses to deeper and stronger layers. Numerical modelling showed that the maximum settlement of the existing foundation reached about 40 mm. After reinforcement with micropiles, settlement decreased to 3.3 mm, demonstrating a substantial improvement in foundation performance. The results confirm the effectiveness of micropiles for strengthening shallow foundations in weak soils and high groundwater conditions. The proposed approach can be applied to the design and rehabilitation of buildings in complex engineering-geological and urban environments.

Keywords: Shallow Foundations; Groundwater Level; Micropiles; Soil Stabilization; Numerical Simulation

1. INTRODUCTION

Shallow foundations are one of the most common structural solutions in construction due to their cost-effectiveness and simplicity of construction. However, their use in weak, water-saturated clay soils, especially where the water table is high, is accompanied by a number of serious geotechnical problems, including significant settlement and reduced structural reliability of buildings. Such conditions are characteristic of the northern regions of Kazakhstan, including Astana, where the influence of seasonal soil freezing is also evident.

Current research in geotechnical engineering is actively focused on the application of numerical methods to analyze the behavior of foundations under complex engineering-geological conditions. One of the most effective tools is the finite element method, which allows for the consideration of nonlinear soil behavior and the interaction between the "soil–foundation" system [1,2].

The PLAXIS 2D software package is widely used to simulate the stress-strain state of foundations and to estimate building settlements. In the work by Abu et al. (2025), it is shown that the use of staged modeling allows for a more accurate account of the development of deformations over time and changes in loading conditions [3]. At the same time, the choice of soil model has a significant impact on the calculation results, as confirmed by the studies of Intui et al. (2025) [4].

Considerable attention is devoted to the analysis of foundation settlements in weak soils. Hu et al. (2021) and Zhou et al. (2019) demonstrated that in soft, water-saturated soils, deformations exhibit a pronounced nonlinear character and depend to a significant extent on the stratification of the soil mass [5,6]. Similar conclusions are presented in the work of Liu and Huang (2023), which notes the localization of settlements in the upper layers of the foundation [7].

A number of studies address the interaction between soil and pile elements. Katzenbach et al. (2016) demonstrated that accounting for soil–structure interaction is a key factor in evaluating the performance of deep foundations [8]. The works of Xu et al. (2024) and Wang et al. (2023) confirm that the use of pile systems allows for the redistribution of loads and a reduction in foundation deformations by engaging deeper soil layers [9,10]. Micropiles as an effective method for foundation reinforcement are discussed in detail in Bruce (2003) and the FHWA (2005) design guidelines, which highlight their ability to bear loads through lateral friction and to increase the stiffness of the system [11,12].

Despite the significant body of research, most studies focus on modeling typical conditions or specific geotechnical problems. At the same time, studies based on the analysis of real-world sites that account for complex engineering-geological conditions—including high groundwater levels and weak soils—are limited. This highlights the need for comprehensive research that combines field data with numerical modeling [13-18].

This paper examines a real-world facility—a warehouse building with an administrative and amenity block (AAB)—located in Astana at 5 Sh. Zhienkulov Street. The facility comprises an industrial block, a two-story administrative building, and a metal canopy. Figure 1 shows a site plan of the facility, illustrating the relative layout of its main elements.

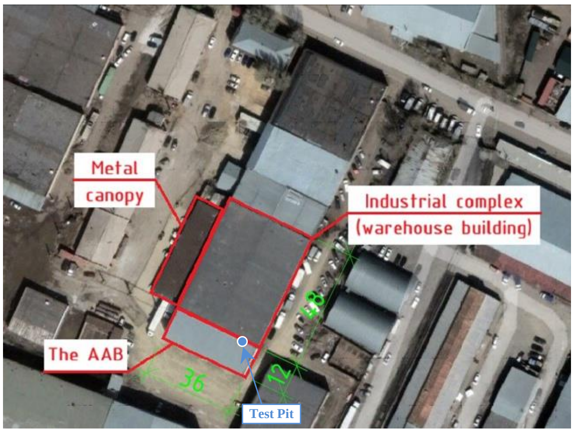

Fig. 1 Site layout diagram

The objective of this study is to conduct a comprehensive assessment of the performance of shallow foundations in weak, water-saturated soils and to evaluate the effectiveness of reinforcing them with micropiles using numerical modeling.

The scientific novelty of this study lies in the integrated application of field investigation, analytical calculations using the BASE software package, and numerical modelling in PLAXIS 2D for a real building founded on weak water-saturated clay soils under high groundwater conditions in Astana. Unlike previous studies based on idealized numerical models, the present research is based on a real engineering project and includes a parametric assessment of micropile reinforcement efficiency.

The remainder of this paper is organized as follows. Section 2 presents the research significance. Section 3 describes the investigated facility, engineering-geological conditions, field investigations, and the numerical modelling methodology adopted in PLAXIS 2D. Section 4 presents and discusses the results of analytical calculations and numerical simulations, including the assessment of micropile reinforcement efficiency. Finally, Section 5 summarizes the main findings and conclusions of the study.

2. RESEARCH SIGNIFICANCE

The scientific significance of this work lies in the acquisition of new data on the behavior of shallow foundations in weak, water-saturated soils with a high groundwater table. Unlike most studies based on computational models, this work utilizes a real-world site, which allows for a more accurate assessment of the behavior of the "subgrade–foundation" system.

The results obtained clarify the mechanisms of settlement formation and stress redistribution when the subgrade is reinforced with micropiles. The practical significance lies in the possibility of applying the obtained relationships and conclusions in design and reconstruction of building foundations under complex engineering-geological conditions.

3. MATERIALS AND METHODS

The subject of this study is an administrative and service building located in Astana. The building is a two-story structure without a basement, rectangular in plan with dimensions of 36×12 m. The structural system consists of a partial frame with load-bearing brick walls and precast reinforced concrete columns. The floor slabs are made of precast reinforced concrete slabs. The foundations consist of strip foundations under the exterior walls and columnar foundations under the columns. The strip foundations are made of FBS blocks with a cross-section of 600×600 mm and are set at a depth of approximately 1.0 m. The columnar foundations are made of monolithic reinforced concrete with base dimensions up to 2200×2000 mm and a depth of approximately 1.4 m.

The technical inspection of the building structures was performed using visual and instrumental methods in accordance with the requirements of SP RK 1.04–101–2012 and included an analysis of the design documentation, on-site inspection, and instrumental measurements. Particular attention was paid to the foundations as the most sensitive elements in conditions of weak, water-saturated soils.

To refine the structural design of the building's underground portion, foundation test pits were excavated (Fig. 2). The work was carried out in April 2023 using both mechanized and manual methods. A total of four test pits were excavated, three of which are located within the administrative building.

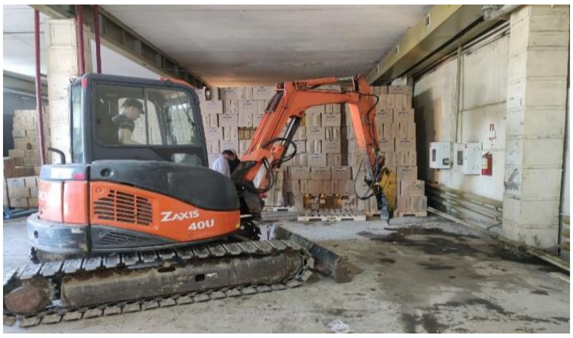

Fig. 2 The process of foundation test pitting

Fig. 3 shows a strip foundation exposed in Test Pit 1. It was determined that the foundation consists of FBS blocks laid on a concrete subgrade. Water accumulation was observed in the test pit at the base level, indicating a high groundwater table.

Fig. 3 Test Pit 1 (strip foundation)

The concrete strength, determined using non-destructive testing methods, corresponds to Class B20 for FBS blocks and Class B25 for monolithic foundations. The first-floor slabs are constructed of monolithic, lightly reinforced concrete approximately 100 mm thick, laid on a crushed stone base.

At the time of the inspection, no signs of uneven settlement were detected. However, an analysis of the operating conditions of the foundations reveals the presence of potential risk factors. These include the shallow depth of the strip foundations, a high groundwater level, and insufficient bearing capacity of the upper layers of the subgrade. Additionally, it should be noted that the foundation footing is located in a zone of seasonal freezing, which may lead to additional deformations during operation. The technical condition of the foundations is generally assessed as limitedly serviceable.

Although seasonal freezing is characteristic of the climatic conditions of Astana, frost-heave effects and freeze–thaw cycles were not explicitly considered in the numerical model. These factors may influence the long-term performance of shallow foundations and should be investigated in future studies using coupled thermo-mechanical analyses.

The engineering-geological conditions of the site are characterized by the presence of fill soils overlying water-saturated loams. The groundwater level is recorded at a depth of 0.8–1.0 m, with a possible seasonal rise. The low modulus of deformation of the loams results in increased compressibility of the subgrade and its sensitivity to loads.

To evaluate the performance of the "subgrade–foundation" system, a numerical simulation was performed using the finite element method in the PLAXIS 2D software package. The analysis was performed under plane strain conditions, which correspond to the operating conditions of strip foundations. The model accounted for the actual dimensions of the foundations, the layered structure of the soils, and their physical and mechanical properties. Soil behavior was described using the Mohr–Coulomb elastic-plastic model.

The numerical model dimensions were selected to minimize boundary effects and ensure realistic stress distribution. A medium finite element mesh composed of 15-node triangular elements was generated automatically and refined in the foundation zone. The staged calculation procedure included generation of initial stresses, activation of foundation elements, and installation of micropiles. The calculations were performed until numerical convergence was achieved at each analysis stage.

Boundary conditions were specified in the standard manner: the bottom boundary of the model was fixed vertically and horizontally, and the side boundaries were constrained against horizontal displacements. The groundwater level was taken into account when establishing the initial stress state.

The study considered two design scenarios: the existing condition of the foundations and a variant involving foundation reinforcement using micropiles. The micropiles were modeled as bored-injected elements operating in a suspended mode due to lateral friction at the "pile–soil" interface, using embedded beam elements. The length of the micropiles was taken to be 8 m, the diameter 0.2 m, and the spacing 0.5 m within a 2-meter-wide zone beneath the foundation footing.

For modelling purposes, the micropiles were assumed to consist of steel reinforcement embedded in cement grout. The micropiles were modelled as friction piles transferring load through the pile–soil interface and engaging the deeper, stiffer soil layers. The geometric layout of the micropiles in plan and section is shown in Figures 4 and 5.

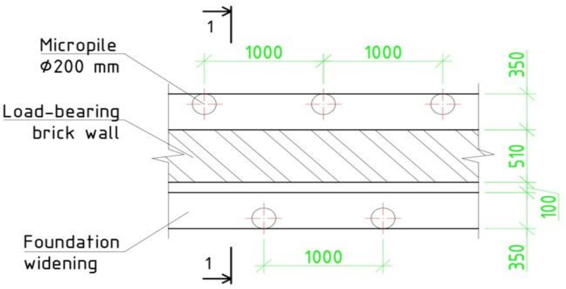

Fig. 4 Layout of micropiles under the strip foundation (plan view)

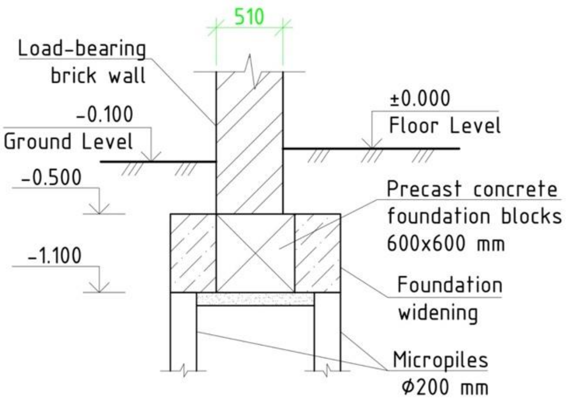

Fig. 5 Structural scheme of foundation strengthening with micropiles (section view)

The methodology employed allows for the assessment of the stress-strain state of the foundation and the determination of the effectiveness of foundation reinforcement under complex engineering-geological conditions.

4. RESULTS AND DISCUSSION

Engineering-geological surveys have shown that the foundation of the site under investigation in Astana consists of fill soils up to 2.2 m thick, overlying water-saturated loam.

A more detailed analysis of the engineering-geological conditions revealed that the site profile consists of three main layers, which differ significantly in their physical and mechanical properties.

The upper part of the profile is formed by fill soils, consisting of loam with inclusions of crushed stone, gravel, and construction debris. These soils are characterized by a heterogeneous composition and are in a stage of natural consolidation, the duration of which can reach several decades. Consequently, their use as a natural foundation without prior preparation is limited.

Beneath the fill soils lie alluvial loams with a thickness of approximately 4.8–5.2 m. This layer has relatively low deformation characteristics. When saturated with water, the modulus of deformation varies between 2.5 and 4.8 MPa, which leads to settlement concentration specifically in this layer. Thus, the upper part of the section largely determines the deformability of the foundation.

In the lower part of the section, eluvial loams up to 8.0 m thick are widespread, characterized by higher strength and deformation properties. The modulus of deformation reaches 14 MPa, which allows this layer to be considered a more reliable foundation for load-bearing. The main design parameters of the soils are given in Table 1.

Table 1. Physical and mechanical properties of soils

Properties	Soil Types		Unit of measurement
	IGE-2. Loam	IGE-3. Loam (eluvial)	
c	23 / 17 / 12	46 / 42 / 36	kPa
φ	21 / 19 / 18	25 / 22 / 21	°
E	4	14	MPa
ρ	2.02	1.84	g/cm³
e	0.545	0.852	-
W	16.4	26.6	%
Sr	0.66	0.64	-

The three values of cohesion and friction angle correspond to normative, design and reduced design parameters according to Kazakhstan geotechnical standards. Additional soil properties, including natural moisture content (W), void ratio (e), and degree of saturation (Sr), are presented to provide a more complete characterization of the engineering-geological conditions.

An analysis of the physical and mechanical properties of the soils reveals a significant contrast in the stiffness of the layers: the upper layer (IGE-2) has low deformability and accounts for the majority of the settlement, whereas the underlying layer (IGE-3), with a modulus of deformation of up to 14 MPa, is capable of effectively bearing the load. This stratification leads to the localization of deformations in the upper part of the section.

It has also been established that the soil and groundwater exhibit corrosive aggressiveness toward metal structures and moderate aggressiveness toward reinforced concrete, a factor that must be taken into account when assessing the long-term reliability of foundations. The groundwater level is shown in Table 2.

For the proposed strengthening solution, corrosion protection of micropiles is ensured by complete grout encapsulation of the steel reinforcement. This approach minimizes direct contact between groundwater and steel elements and contributes to the long-term durability of the reinforcement system under aggressive groundwater conditions.

Table 2. Groundwater conditions

Borehole	Ground elevation, m	Ground water depth, m	Ground water level, m
1	354.8	1.0	353.8
2	354.8	0.8	354.0

The results of the foundation calculations performed in BASE are presented in Table 3.

Table 3. Calculation results for foundations

Parameter	Column footing	Strip footing
K (deformation)	0.48	0.98
K (strength)	0.30	0.79
Design resistance, tf/m²	20.41	16.06
Max. stress, tf/m²	9.81	15.67

The results of calculations performed in the BASE software package show that the strip foundations are operating near the ultimate limit state in terms of deformation (K = 0.98), whereas a safety margin remains in terms of strength (K = 0.79). This means that the limiting factor is not the bearing capacity, but the high compressibility of the foundation. The proximity of the maximum stresses to the design resistance (σmax ≈ R) indicates that the foundation is operating under ultimate loading conditions, under which even minor changes in external factors can lead to an increase in deformations.

An analysis of the stress distribution (Fig. 6) shows that stresses are concentrated directly beneath the foundation footing. This indicates an inefficient foundation design, in which the load is borne primarily by the upper, weaker soil layer without the involvement of stronger soils. From an engineering standpoint, this leads to accelerated deformation and reduced operational reliability.

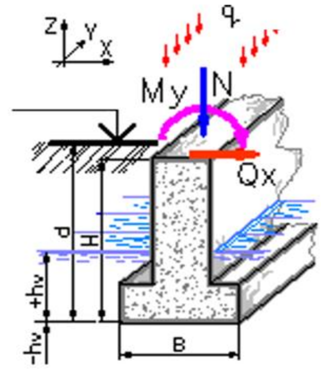

Fig. 6 Distribution of principal stresses in the foundation in the BASE software package

To improve the reliability of the foundation, a numerical simulation of the reinforcement using micropiles was performed using the PLAXIS 2D software package (Fig. 7).

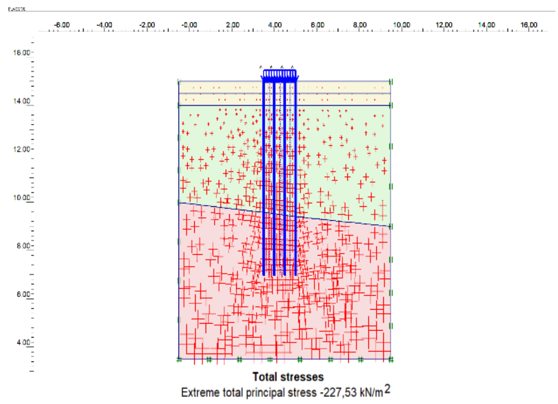

Fig. 7 Distribution of principal stresses in the foundation (PLAXIS 2D)

Figure 7 shows the distribution of principal stresses in the foundation, obtained from numerical simulations in PLAXIS 2D. It can be seen that the maximum stresses are concentrated directly beneath the foundation footing, forming a zone of localized loading.

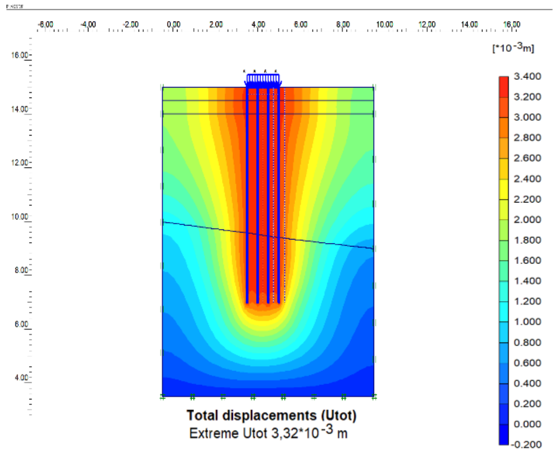

Fig. 8 Design settlement of a reinforced foundation (PLAXIS 2D)

The simulation results show that the maximum settlement of the foundation does not exceed 3.3 mm. This value indicates a significant increase in the system's stiffness. This effect is due to the redistribution of stresses and the involvement of denser soil layers (IGE-3), which have a higher modulus of elasticity. As a result, stress concentration in the upper weak layer is reduced, leading to a decrease in the overall deformability of the foundation.

For comparison purposes, an additional numerical analysis was performed for the existing strip foundation without micropile reinforcement. The results showed that the maximum settlement of the unreinforced foundation reached approximately 40 mm. After installation of micropiles, the settlement decreased to 3.3 mm, corresponding to a reduction of about 92%. This demonstrates the high efficiency of the proposed reinforcement solution under the considered engineering-geological conditions.

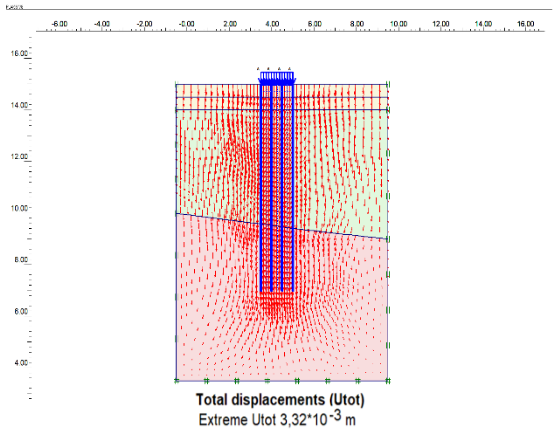

Fig. 9 Soil displacement vectors

The displacement vectors (Fig. 9) confirm a change in the foundation's behavior. In the initial state, vertical deformations predominate in the weak layer, whereas after reinforcement, a decrease in both vertical and horizontal displacements is observed. This indicates an increase in the stability of the soil mass and a reduction in lateral consolidation.

The results obtained are consistent with recent studies on numerical modeling of foundations. In particular, Abu et al. (2025) demonstrate that the use of PLAXIS 2D allows for an accurate assessment of changes in the stress-strain state of the foundation under various loading scenarios [3]. The importance of soil model selection is also confirmed in the studies by Intui et al. (2025), which note that accounting for nonlinear behavior significantly affects settlement predictions. In the present study, the use of the Mohr–Coulomb elastic-plastic model yielded results reflecting the deformation behavior of water-saturated soils [4].

The identified localization of deformations in the upper weak layer is consistent with the results of Hu et al. (2021) and Zhou et al. (2019), which show that in the presence of layers with contrasting stiffness, the majority of settlement occurs in the most compressible layer [5,6]. A similar effect is described in the work of Liu and Huang (2023), where a concentration of deformations near the surface is noted [7]. The obtained results on reinforcement efficiency correspond to the conclusions of Katzenbach et al. (2016) [8], as well as Xu et al. (2024) and Wang et al. (2023), which show that the inclusion of pile elements leads to a redistribution of stresses and the involvement of deeper soil layers in the load-bearing process [9,10].

The mechanism of micro-pile performance identified in this study confirms the findings presented in Bruce (2003) and the recommendations of the FHWA (2005), according to which settlement reduction is achieved through load transfer via the lateral surface of the piles [11,12]. It should be noted that in most published studies, the reduction in settlement when using micropiles ranges from 30% to 70%. In the case under consideration, a more pronounced effect is observed, which may be due to the significant contrast in the stiffness of the layers (E = 4 and 14 MPa), as well as the high groundwater level, which enhances the effect of load transfer to depth.

A sensitivity analysis was performed to evaluate the influence of the main micropile parameters on foundation settlement. The analysis focused on the effect of micropile diameter and length under identical loading and soil conditions. To quantitatively assess the influence of the main geometric parameters of micropiles (length and diameter), a sensitivity analysis was performed; the results are shown in Figures 10 and 11.

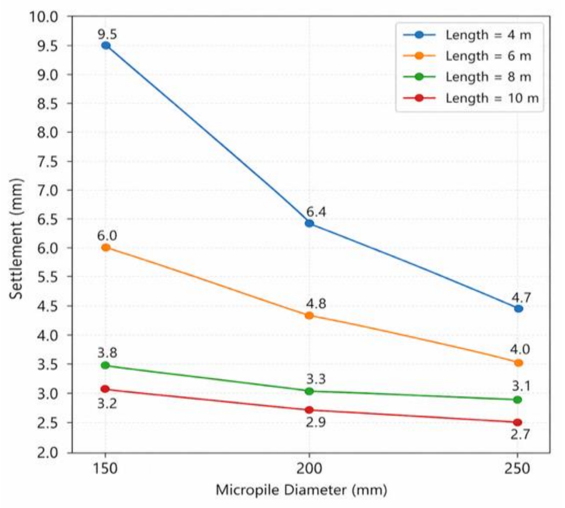

Fig. 10 Effect of micropile diameter on foundation settlement for different micropile lengths

Fig. 10 shows the relationship between foundation settlement and micropile diameter for different micropile lengths. The results indicate that increasing the micropile diameter leads to a moderate reduction in settlement. However, the influence of micropile length is significantly more pronounced, particularly when the micropiles reach the deeper and stiffer soil layer.

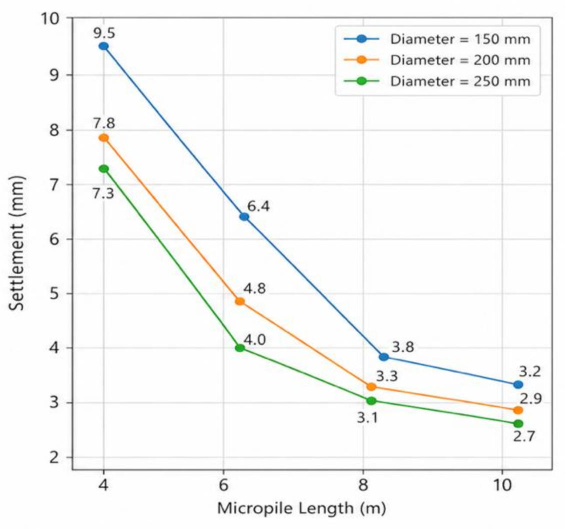

Fig. 11 Effect of micropile length on foundation settlement

Fig. 11 shows the effect of micropile length on foundation settlement. Increasing the length from 4 to 10 m leads to a significant reduction in settlement from 9.5 to 2.7 mm. The most significant reduction in settlement is observed at a length of 8 m, which is associated with the involvement of a stiffer underlying soil layer.

A comparison of the results (Fig. 10 and Fig. 11) shows that the length of the micropiles has a significantly greater effect on reducing settlement than their diameter. This confirms that the primary mechanism for increasing foundation stiffness is the redistribution of stresses to deeper and stronger soil layers, rather than an increase in the cross-sectional area of the piles.

Thus, it has been established that under the conditions under consideration, the deformability of water-saturated soils is the determining factor. The use of micropiles allows for a significant change in the behavior of the foundation, ensures stress redistribution, and increases the reliability of the foundations.

Seasonal fluctuations of groundwater level may influence the stress-strain state of shallow foundations by increasing soil saturation and reducing soil stiffness. In addition, long-term creep behaviour of water-saturated clay soils may contribute to gradual settlement development during the service life of the structure. Although these effects were not explicitly considered in the present numerical analysis, they should be taken into account in future investigations aimed at evaluating the long-term performance of reinforced foundations.

5. CONCLUSION

This study presents a comprehensive assessment of the performance of shallow foundations in conditions of weak, water-saturated soils and high groundwater levels, using a real-world project in Astana as a case study. It has been established that strip foundations operate near the limit state in terms of deformation (K = 0.98), while a sufficient safety margin remains in terms of strength, indicating the dominant role of the deformability of the subsoil.

Numerical modeling indicates that the use of micropiles can significantly alter the behavior of the "subgrade–foundation" system by promoting load redistribution to deeper and more competent soil layers. As a result, the maximum subgrade settlement is reduced to 3.3 mm, indicating a significant increase in the stiffness and stability of the system.

The obtained results suggest that the high compressibility of water-saturated soils combined with a high groundwater level is one of the key factors influencing foundation performance under the considered conditions. The use of micropiles effectively compensates for this factor by forming a "soil-pile" composite system that redistributes the load to deeper and stronger layers. This is particularly important when reinforcing building foundations in the confined conditions of urban development and under complex engineering-geological conditions, where the use of traditional reinforcement methods is limited.

The parametric analysis demonstrated that micropile length has a significantly greater influence on settlement reduction than micropile diameter. The most effective performance was achieved when the micropiles penetrated the deeper and stiffer eluvial loam layer, resulting in more efficient stress redistribution and improved foundation stiffness.

The practical significance of this work lies in the applicability of the proposed approach to the inspection and renovation of existing buildings located on weak, water-saturated soils.

In the future, it would be advisable to conduct studies using more complex soil models that account for the nonlinear relationship between stiffness and time-dependent effects, as well as to verify the results based on field observations.

The conclusions presented in this study are based on numerical simulations performed using the Mohr–Coulomb constitutive model and the assumptions adopted in the PLAXIS 2D environment. Therefore, the obtained results should be interpreted within the limitations of the selected modelling approach. Future studies may employ more advanced constitutive models and three-dimensional analyses to further improve the accuracy of the predictions.

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