STU SvF
SLOVAK UNIVERSITY OF TECHNOLOGY IN BRATISLAVA
FACULTY OF CIVIL ENGINEERING

Slovak Journal of Civil Engineering

Vol. 33, 2025, No. 4, 31 – 41
DOI: 10.2478/sjce-2025-0025

NUMERICAL STUDY OF THE LOAD TRANSFER IN PILED RAFT FOUNDATIONS

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Abstract

Piled raft foundations are a reliable solution for improving load distribution and minimizing settlement, particularly in soils where shallow foundations are inadequate. This study focuses on the performance of floating piled raft systems in sandy soils, where controlling settlement is critical. A calibrated three-dimensional finite element (FE) model was developed and validated using experimental load–settlement data to investigate the effect of key parameters, including the number of the pile and the stiffness of the piled-raft foundations. The results show that an optimal configuration of 10 piles achieves a balanced load-sharing ratio of approximately 50% between the raft and piles, which effectively minimizes the settlement without any unnecessary structural redundancy. Beyond this point, additional piles reduce settlement by only 3–5%. The stress distribution analysis highlights the importance of raft–soil interactions, while parametric studies demonstrate how pile numbering and piled-raft stiffness affect the performance of the foundations. This research reinforces the value of numerical modeling as a predictive tool and offers practical design recommendations for cost-effective and sustainable foundation systems in sandy ground conditions.

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Key words

- Pile Raft Foundation,
- Load-Sharing Ratio,
- Sandy Soils,
- Numerical Modelling.

1 INTRODUCTION

In geotechnical engineering, the performance of shallow foundations is commonly constrained by the deformability and limited bearing capacity of underlying soils, especially in cases where compressible or loose layers prevail (Burland et al., 1977; Gudehus and Weißenbäck, 1996). Previous investigations have shown that shallow foundations on sandy soils, which are characterized by their granular structure and low cohesion, can be particularly susceptible to excessive settlement, as well as potential liquefaction under seismic or dynamic loads (Hooper, 1979; Vanapalli and Mohamed, 2013). These factors compromise both the serviceability and stability of structures, thereby necessitating robust foundation solutions that go beyond simple raft or footing systems (Malviya et al., 2023).

To tackle these challenges, engineers often employ deep foundations, such as pile groups or piled rafts, to transfer loads to more competent strata and to control settlement (Fellenius, 2006; Long, 2010). Piled rafts in particular have become standard practice in complex geotechnical projects as they capitalize on the combined bearing action of both the raft and piles (Poulos, 2001; Katzenbach et al., 1998; Akl et al., 2014; Hirakawa et al., 2020). Numerous studies have stressed that incorporating piles beneath a raft can substantially enhance load-bearing capacity while reducing overall and differential settlements (Clancy and Randolph, 1993; Randolph, 1994; Le Duc et al., 1997; Teji and Ashango, 2023). Historically, however, conservative design methods have assumed that piles alone support the entire structural load, effectively neglecting any beneficial load sharing offered by the raft (Bandyopadhyay et al.; Reul and Randolph, 2004). Such assumptions often lead to excessive pile counts and unnecessarily high construction costs (De Sanctis and Mandolini, 2006; Ojha and Srivastava, 2021). Instead, modern approaches treat the foundation as an integrated system, accounting for pile–soil, raft–soil, and pile–raft interactions, to achieve more balanced designs (Misra and Basu, 2011; Katzenbach et al., 2005).

A growing body of work affirms the merits of piled raft foundations across various soil conditions. The concept dates back to seminal observations that the raft itself carries a notable proportion of the load, even in pile-supported systems (Hooper, 1979; Burland et al., 1977). In sandy soils, Al-Mosawi et al. (2011) showed through laboratory tests that combined piled rafts can outperform conventional pile groups or isolated rafts, particularly when the length and spacing of piles are optimized. Laboratory experiments by Bralović et al. (2023) further confirmed that standard design methods often overestimate pile demands and fail to exploit a raft's inherent load-bearing capacity. Additional studies of piled rafts subjected to vertical loading, such as those by Bandyopadhyay et al (2020) and Fattah et al. (2024), in layered sandy soils, have demonstrated that selective pile placement improves not only bearing capacity but also the overall load distribution beneath the raft.

Centrifuge model tests, in particular, have provided invaluable insights into the mechanisms governing raft-pile-soil interactions (Horikoshi and Randolph, 1997; Conte et al., 2003). These experiments reveal that foundation geometry, the number of piles, and soil stiffness critically affect how loads are transferred to deeper strata (Azizkandi et al., 2018; Boulanger et al., 2003). In liquefiable and laterally spreading soils, for instance, dynamic centrifuge tests highlight the importance of pile group configurations that account for both vertical and lateral load components (Boulanger et al., 2003). Similarly, small-scale model tests by Baziar et al. (2009) and their numerical counterparts underscore how factors like raft thickness and pile diameters can modulate stress distribution within a foundation system.

Full-scale investigations and long-term monitoring also support these findings. Field measurements by Yamashita et al. (2011) and Yamashita et al. (2014) on high-rise buildings in Japan illustrate that piled rafts yield a satisfactory performance when subjected to sustained loads, provided that the settlement contours and load-sharing ratios are carefully accounted for. Studies on tall buildings constructed using top-down methods similarly reported better settlement control through combined foundation systems (Hirakawa et al., 2020; Katzenbach et al., 1998). Elsewhere, Bernardes et al. (2024) documented the geotechnical behavior of a piled raft in tropical lateritic soils; they found a substantial difference in raft–soil contact stresses between the initial and stabilized phases of loading. Such long-term monitoring projects confirm that adopting a piled raft design can be both structurally beneficial and cost-effective, especially in heterogeneous or weak soils.

Besides experimental and field-based work, numerical modeling has grown into an essential tool for understanding piled rafts (Small et al., 2006; Zhang and Small, 2002; Garcia and Albuquerque, 2019; Zhou et al., 2016). Using finite element or finite difference methods, researchers can simulate three-dimensional interactions between a raft, piles, and soil, by capturing nonlinearities in the stiffness of soil and the development of plastic zones under loading (Lee and Chung, 2005; Oh et al., 2008; Elsobky et al., 2021). Recent practical applications of such techniques include high-rise structures, such as the Nivy Tower in Bratislava, where finite element analysis was used to assess long-term settlement behavior and validate design assumptions under real loading conditions (Chalmovský et al., 2024). These models confirm that parameters such as pile arrangement, spacing, and interface behavior have a significant effect on both total and differential settlements. Such analyses confirm that design parameters, particularly the number and arrangement of piles, strongly affect both total and differential settlements (Lee et al., 2015; De Sanctis and Mandolini, 2006). Moreover, parametric studies have demonstrated that optimizing pile spacing can drastically improve load-sharing efficiency, thus reducing reliance on an overly conservative pile count (Le Duc et al., 1997; Nguyen et al., 2012; Shamsi Sosahab et al., 2019; Panday et al., 2023).

Other analyses have further highlighted the role of sustainability and resource management in foundation design. Misra and Basu (2011) introduced sustainability metrics that can be employed to evaluate the ecological footprint and economic viability of deep foundations; they emphasized that combined piled rafts significantly reduce material use. This perspective was echoed by Ojha and Srivastava (2021), who advocate combined piled-raft foundations for weak alluvial soils as a sustainable alternative to conventional deep foundations. Indeed, advanced geotechnical design paradigms encourage the use of integrated methods such as the combined pile-raft foundation (CPRF) to achieve both economic and environmental objectives (Katzenbach et al., 2005; Tarenia et al., 2023).

To accommodate uncertainties or varying soil conditions, adaptive optimization techniques have also been proposed. For example, Yuan et al. (2023) developed a variable pile-spacing method to automatically refine foundation geometry, while Teji and Ashango (2023) used 3D numerical simulations in layered soil to identify optimal pile arrangements. Similarly, advanced finite element codes allow for the limit state design of structural parts in conjunction with soil behavior (Gudehus and Weißenbäck, 1996; Vanapalli and Mohamed, 2013). Such approaches not only ensure safety but also encourage efficient usage of materials and construction time (Randolph, 1994; Misra and Basu, 2011). Against this backdrop, the present study offers an advanced numerical examination of floating piled raft foundations in sandy soils by specifically calibrating three-dimensional finite element (FE) models with empirical data from controlled laboratory tests (El-garhy et al., 2013). Emphasis is placed on analyzing the load distribution, raft–pile interactions, and settlement characteristics in a systematic manner, where supplemented earlier findings from small-scale experiments (Bralović et al., 2023; Fattah et al., 2024) and real-world monitoring (Yamashita et al., 2011; Yamashita et al., 2014). Moreover, the comprehensive simulations herein incorporate guidelines suggested by earlier numerical studies (De Sanctis and Mandolini, 2006; Poulos and Small, 2007) to capture nonlinear soil behavior and possible raft bending under a load. By integrating these multifaceted approaches, while range from model tests (Bandyopadhyay et al.) and field observations (Bernardes et al., 2024) to sophisticated computational algorithms (Zhang and Small, 2002; Zhou et al., 2016), the study aims to refine existing design recommendations, mitigate settlement issues, and support more sustainable foundation solutions in challenging sandy environments.

Building on these comprehensive experimental and numerical studies, this research presents an advanced numerical investigation into the load distribution and settlement behavior of floating piled raft foundations in sandy soils. The study employs three-dimensional finite element modeling, which has been rigorously calibrated and validated against empirical laboratory data obtained from controlled experimental tests. These experimental findings, including force-displacement curves and settlement profiles, serve as benchmarks for verifying the numerical predictions, thus ensuring robust and realistic simulations. The numerical validation is specifically based on the experimental study conducted by El-Garhy et al. (2013), which provides critical insights into the performance of raft on settlement-reducing piles under various loading conditions. The numerical model replicates key soil-foundation interaction mechanisms by integrating nonlinear soil behavior, pile-soil friction, and raft-pile coupling effects. The results of validation confirm a strong correlation between the experimental observations and simulated outcomes, particularly in load-sharing ratios and settlement reduction trends.

Optimal pile spacing is critical in piled-raft design as it governs interaction effects and load-sharing efficiency. Parametric finite-element studies (IJERT, 2020) have varied the pile spacing from 2.5D to 6D and observed a near-linear increase in the settlement and a decrease in the pile-load share with increased spacing, which indicates that 2.5D spacing yields the most effective reduction in settlement while maximizing load-sharing. The findings reinforce the effectiveness of piled rafts in optimizing load-bearing efficiency, reducing settlement, and enhancing the economic feasibility of foundation design in sandy environments. This study contributes to the refinement of design guidelines by providing quantifiable insights into load-sharing characteristics, differential settlement mitigation, and the effect of the thickness of the raft and the spacing of the piles. By bridging the gap between experimental research and numerical modeling, the paper delivers practical recommendations for geotechnical engineers aiming to achieve cost-effective, high-performance foundation solutions.

2 MATERIAL PROPERTIES

This study adopts material parameters consistent with the experimental work of El-Garhy et al. (2013) to ensure coherence between laboratory tests and finite element simulations. Two primary materials are considered, medium sand as the foundation soil and steel for the structural components (raft and piles)

2.1 Medium Sand

In the simulation, the medium sand was modeled using an elastic, perfectly plastic constitutive model based on the Mohr-Coulomb failure criterion. This model provides a reasonable representation of the stress–strain behavior of medium sand under drained loading conditions, particularly within the serviceability range, where deformations remain small and well within the elastic domain. As such, the response of the soil predominantly remains in the elastic range throughout the loading process. The following key material properties were incorporated into the model:

- Elastic modulus: 37 MPa, representing the stiffness of the sand under loading.
- Poisson's ratio: 0.30, accounting for lateral strain effects.
- Unit weight: 15 kN/m³, affecting the stress distribution and overburden pressure.
- Internal friction angle: 33°, reflecting the shear strength and bearing capacity of the soil.

2.2 Steel

The raft and piles are modeled as linear elastic steel elements, reflecting the rigidity and high strength of the structural system used in scaled experiments. The following properties were adopted:

- Elastic modulus: 210,000 MPa, enabling accurate modeling of the structural rigidity.
- Poisson's ratio: 0.20, accounting for any lateral deformation.
- Unit weight: 78.5 kN/m³, included in the model to represent self-weight contributions.

The material properties used in the numerical model are summarized in Table 1.

Tab. 1 *Material Properties*

Parameters	Medium Sand	Steel
Modulus of elasticity (MPa)	37	210,000
Poisson ratio (-)	0.3	0.2
Unit weight (kN/m³)	15	78.5
Internal friction angle (°)	33	-

3 METHODOLOGY AND MODEL

This study has utilized a calibrated three-dimensional finite element (FE) model to investigate the behavior of floating piled raft foundations embedded in sandy soils. The numerical simulations were performed using PLAXIS 3D. The modeling approach replicates the physical testing conditions to provide a robust framework for analyzing the load transfer, settlement characteristics, and soil–structure interaction.

3.1 Numerical Model and Assumptions

The foundation system was modeled as a rigid steel raft supported by multiple steel piles within a homogeneous sandy soil medium. The soil behavior was captured using a Mohr-Coulomb elastoplastic model, which is appropriate for drained loading conditions and small-strain responses. The raft and piles were treated as linear elastic components. Interface elements were introduced at all the raft–soil and pile–soil boundaries to simulate realistic contact behavior, including any slippages and partial separations. A fully three-dimensional configuration was maintained without geometric simplifications to preserve fidelity in the load paths and stress distribution.

3.2 Geometric Model and Experimental Setup

The geometry of the model followed the experimental setup by El-Garhy et al. (2013). A cubic soil domain with dimensions of 1000 × 1000 × 1000 mm was used to represent the test box. The raft was modeled as a steel plate measuring 300 × 300 × 10 mm, and the piles were represented as steel rods with a diameter of 10 mm and a length of 300 mm. Pile groups of varying counts (1 to 16) were arranged in a square grid pattern. The soil and structural properties were directly derived from experimental data for an accurate comparison.

Tab. 2 *Material Properties*

Description	Dimensions [mm]
Rigid test box	1000 x 1000 x 1000
Plate	300 x 300 x 10
Steel rods Diameter	10
Steel rods Length	300
Steel rods Spacing (2.5D)	25

3.3 Boundary Conditions and Loading

The base of the soil domain was fully fixed to simulate a rigid boundary, while the lateral boundaries were constrained horizontally but free to move vertically. A vertical point load was applied incrementally at the center of the raft to replicate the laboratory loading procedure. The settlement was recorded at each increment to generate load–displacement curves and evaluate the deformation behavior under increasing loads.

3.4 The Calibration and Validation of the Model

The calibration of the model was achieved by adjusting the interface reduction factor Rinter and comparing the numerical force–displacement curves to the experimental results. The model was validated by comparing both the total settlement and load-sharing ratios across different pile configurations. A root mean square error (RMSE) of approximately 0.45 kN and a deviation within ±8% of the experimental results confirmed the model's reliability in simulating load-transfer mechanisms in sandy soils.

3.5 Load-Sharing Computation and Analysis

At each loading step, the model calculated the proportion of the vertical load carried by the raft and piles. The pile load-sharing ratio, α_p, is defined in equation 1:

$$\alpha_p = \frac{P_p}{P_{pr}} = 1 - \frac{P_r}{P_{pr}} \quad (1)$$

Where:
α_p = Load-sharing ratio of piles
P_p = Vertical load carried by the piles
P_r = Vertical load carried by the raft
P_{pr} = Total vertical load applied on the foundation system

3.6 Load-Sharing Computation and Analysis

A targeted parametric analysis was performed to quantify the effect of the pile count on the foundation's performance. Configurations ranging from a raft-only case (0 pile) to systems with 1, 4, 9, and 16 piles were examined; all were arranged in a uniform spacing of 2.5 D. For each scenario, we recorded the total settlements and calculated the pile-to-raft load-sharing ratio. The systematic variations revealed how even a single pile markedly reduced peak settlement and how intermediate layouts (4 and 9 piles) progressively improved both the settlement's uniformity and load-transfer efficiency.

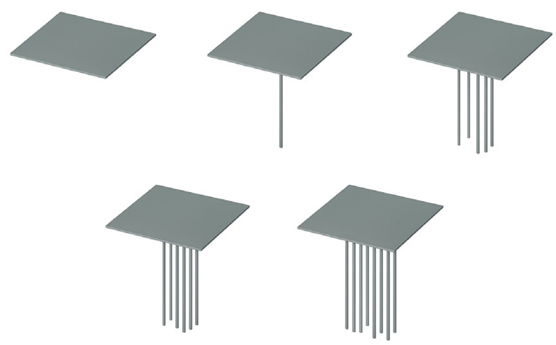


Fig. 1 *FEM model*

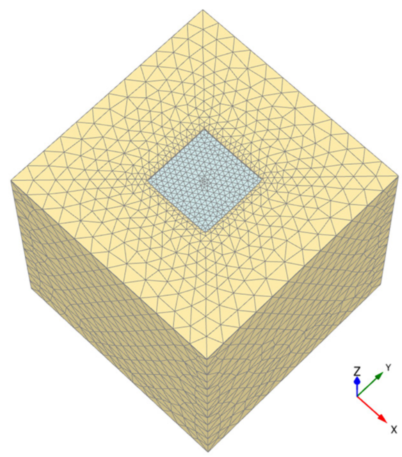


Fig. 2 *Mesh generation*

3.7 Interfaces

Zero-thickness interface elements were applied at all the raft–soil and pile–soil contact surfaces to realistically model the behavior of the interaction. These elements, which are shown in green in Figure 3, allow for slips and partial separations between the structural components and the soil by capturing essential frictional and shear transfer mechanisms. An interface reduction factor of R_{inter} = 0.75 was used to scale the shear strength of the interface relative to the surrounding soil. This value was calibrated to reflect the experimental observations and ensure the accurate simulation of the load transfer and settlement behavior.

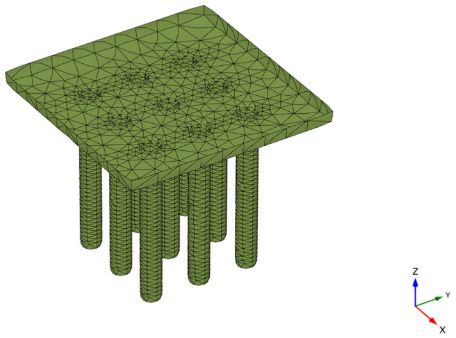


Fig. 3 *The interface elements*

4 RESULTS AND DISCUSSION

4.1 Settlement Behavior of the Piled Raft Configurations

Figure 4 presents the contour plots of the vertical settlement of the piled raft foundations under the varying pile configurations, specifically with 1, 4, 9, and 16 piles. These visualizations highlight the effectiveness of increasing pile numbers in mitigating total and differential settlements.

The single-pile configuration (Figure 4d) exhibits a sharply localized settlement zone concentrated beneath the raft's center. The raft experiences a bowl-shaped deformation profile, which indicates that most of the load was transferred directly through the raft to the soil, with a minimal contribution from a single pile.

With 4 piles (Figure 4c), the settlement pattern became slightly more diffused, but the central concentration remained dominant. While the additional piles begin to support some of the load, the raft still are the majority, which led to a moderate differential settlement across its surface.

In the 9-pile configuration (Figure 4b), the settlement contours displayed a significantly more uniform distribution. The central peak settlement was reduced, and the peripheral uplift was notably minimized. This suggests an enhanced interaction between the raft, piles, and soil, with the load more evenly shared among the system components.

The 16-pile setup (Figure 4a) further improved the uniformity of the settlement and produced a flatter deformation profile. The magnitude of the settlement was lowest in this case, and the differential settlement was minimal. However, when compared to the 9-pile system, the reduction in total settlement was marginal, thereby indicating diminishing returns from any additional piles.

4.2 Load-Displacement Response and Validation of the Model

The load–displacement behavior of the foundation system was assessed for various pile configurations using the calibrated finite element (FE) model. Figure 5 illustrates the vertical load–settlement curves generated through the numerical simulations and captures the non-linear settlement response under increasing axial loads. This non-linearity reflects the progressive mobilization of the soil's resistance and the interactive behavior between the piles, raft, and surrounding soil medium.

The numerical results were rigorously validated against the experimental data obtained from the physical model tests conducted by El-Garhy et al. (2013), as shown in Figure 6. A strong agreement was observed across all the configurations, with deviations in the peak load capacity remaining within ±8% of the experimental values. The root mean square error (RMSE) between the numerical and experimental load–settlement responses was approximately 0.45 kN, which affirmed the model's robustness and reliability.

The comparison further confirms that the model accurately captures key interaction mechanisms such as the pile–soil friction and raft–soil contact behavior. Notably, the transition from raft-dominant to pile-supported load transfer is well represented; it aligns closely with the physical observations. For instance, in configurations with fewer piles, the raft primarily resisted the applied load, while in systems with 9 or more piles, a significant shift occurred with the piles absorbing a larger portion of the load.

4.3 Stress Distribution and Contact Pressure Analysis

Figures 7 through 10 present the effective stress contour maps beneath the raft for different pile configurations specifically for 16, 9, 4, and 1 pile, respectively. These visualizations illustrate how stress is transferred from the foundation system into the underlying sandy soil and how the presence and number of piles affect this distribution.

Figure 7 shows the stress distribution for the 16-pile configuration. The stress is distributed relatively uniformly beneath the raft, with visible interaction zones between the adjacent piles. The contour map reveals a broad zone of moderate stress beneath the raft, which indicates the strong raft–soil contact and substantial stress diffusion through both the piles and the raft base. This reflects an optimized load-transfer mechanism with minimal concentration points, thereby leading to a reduced differential settlement.

Figure 8, which corresponds to the 9-pile configuration, displays a similarly well-distributed stress pattern, albeit with slightly more pronounced stress concentrations beneath the central region compared to the 16-pile case. The raft–soil contact remains significant and affirms that even at this pile count, the raft contributes meaningfully to the load transfer and supports the model's finding of a near-optimal 50:50 load-sharing ratio.

Figure 9 shows the 4-pile scenario, where the stress concentration becomes more localized around the pile tips, with a noticeable reduction in the raft–soil interaction across the span. The central area of the raft exhibits higher stress zones and indicates that while the piles help in the load transfer, the raft is still bearing a disproportionate share of the load. This results in a less efficient stress diffusion and higher potential for localized settlement.

Figure 10 depicts the case with a single pile. Here, the stress is highly concentrated directly beneath the lone pile, with a minimal amount of stress observed under the rest of the raft. This configuration leads to a highly uneven load transfer mechanism and significant bending of the raft. The absence of an effective stress distribution under the raft confirms that a single pile absorbs only a small portion of the load, which causes the raft to experience elevated stress and larger settlement values.

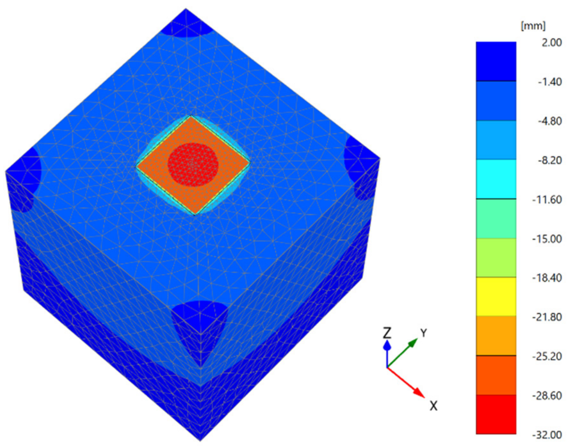
4.4 Load-Sharing Efficiency

Throughout this study, the pile spacing was held constant at 2.5D to isolate the effects of these two parameters. The primary focus was to understand how increasing the number of piles affects the distribution of vertical loads between the raft and the piles.

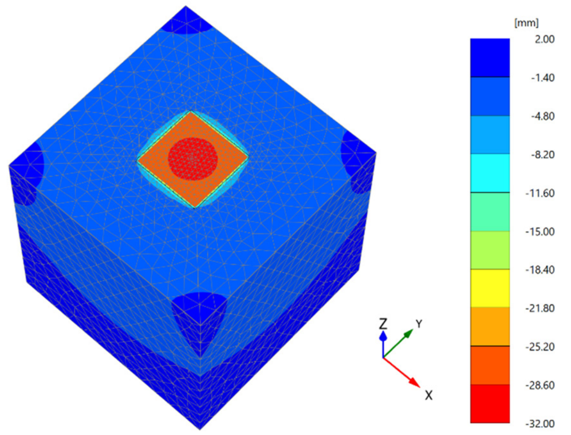
Figure 11 presents the evolution of the load-sharing ratio as the number of piles increased from 1 to 16. The results reveal a distinct non-linear trend. At low pile counts, the raft assumes the majority of the load applied, which underscores its primary structural role in early configurations. For example, in the single-pile case, the raft carried approximately 85% of the load, with only a minor contribution from the pile.

As the number of piles increases, the share of the load transferred to the piles rises significantly. A particularly sharp transition occurs between 1 and 4 piles, where the pile load contribution jumps from around 15% to nearly 35%. This trend continues with diminishing intensity up to 9 and 10 piles, where the load-sharing reaches near equilibrium, approximately 50% by the raft and 50% by the piles. This balance represents the optimal configuration in terms of structural efficiency and material use.

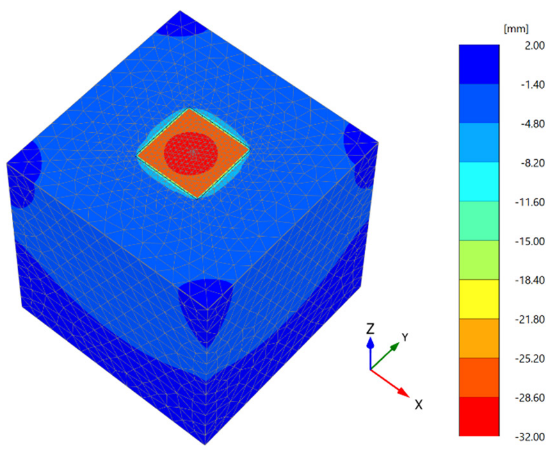
Beyond 10 piles, the incremental gain in the pile load-share begins to plateau. With 16 piles, the piles carry about 65% of the total load. However, this increased load contribution does not translate into significant improvements in control of the settlement. In fact, the additional reduction in settlement from 10 to 16 piles is marginal, only about 3–5%. This finding indicates diminishing returns with respect to both the structural performance and cost-efficiency when exceeding a 10-pile configuration.



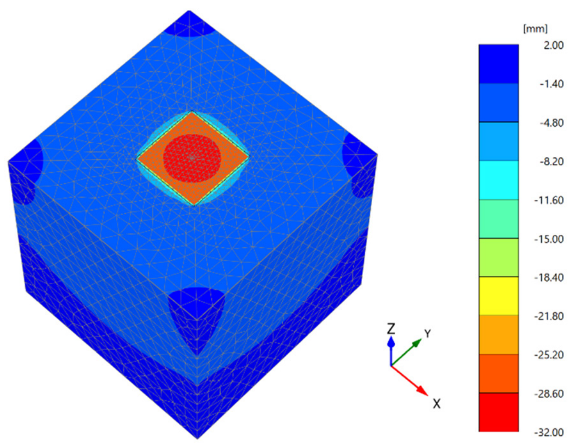
a) 16 Piles



b) 9 Piles



c) 4 Piles



d) 1 Pile

Fig. 4 *Contour map of the settlement based on the FEM model*

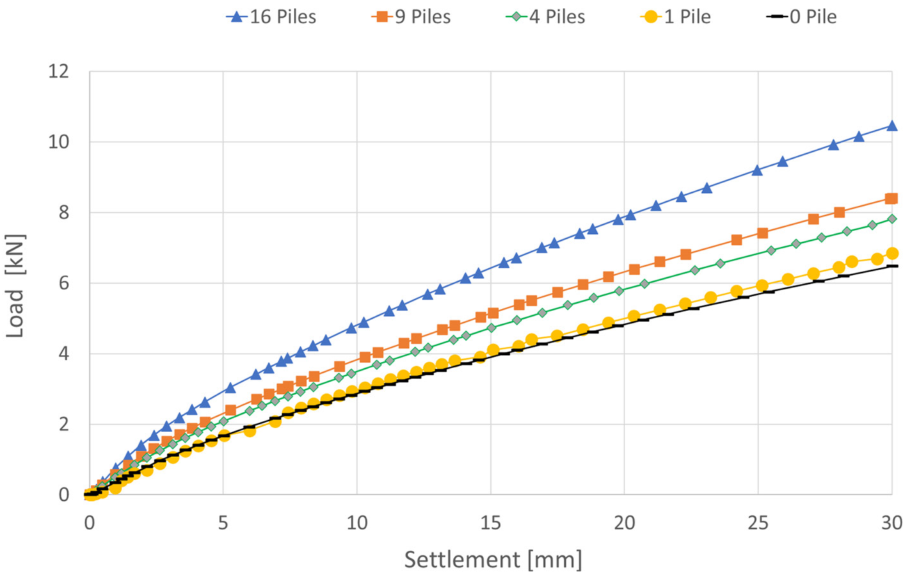


Fig. 5 *Vertical Load-Settlement curve based on the FEM model*

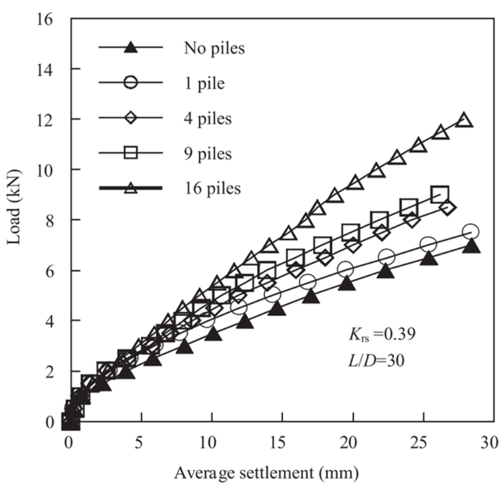


Fig. 6 *Vertical Load-Settlement curve based on the experimental test*

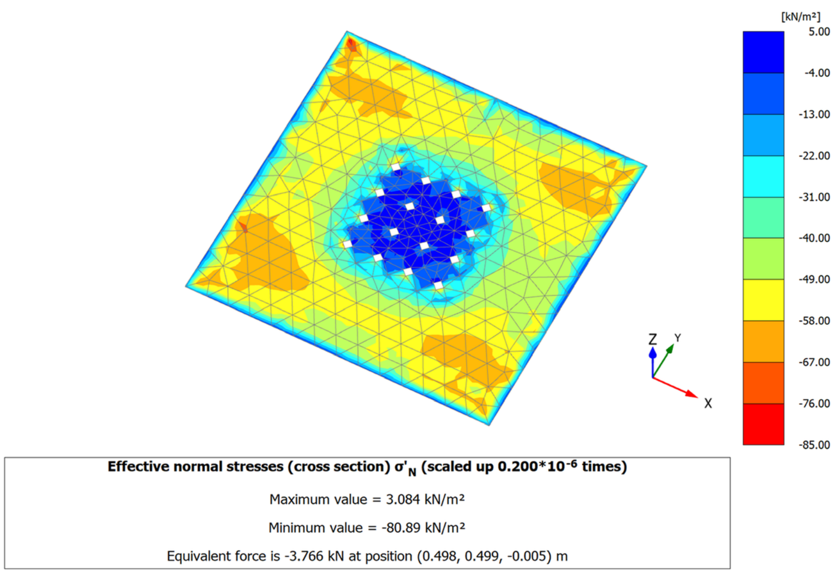


Fig. 7 *Contour map of the effective stress shared by the raft foundation in the case of 16 piles*

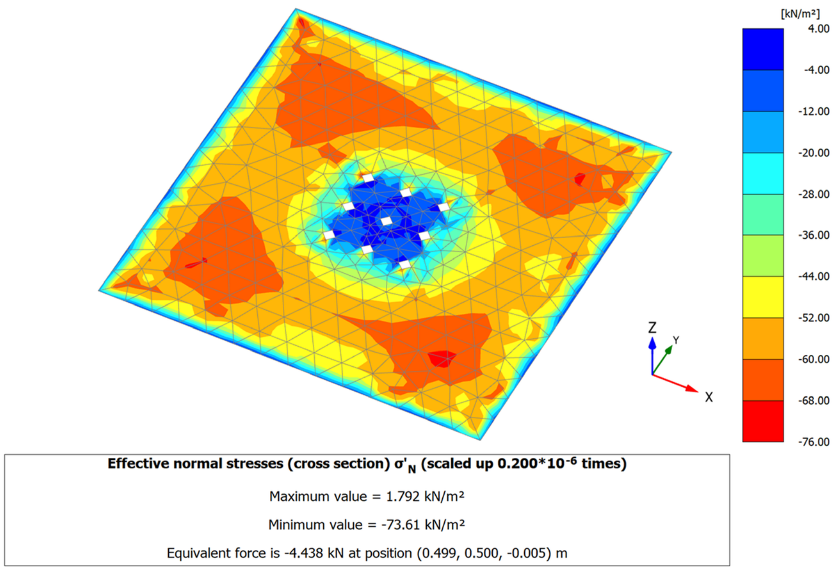


Fig. 8 *Contour map of the effective stress shared by the raft foundation in the case of 9 piles*

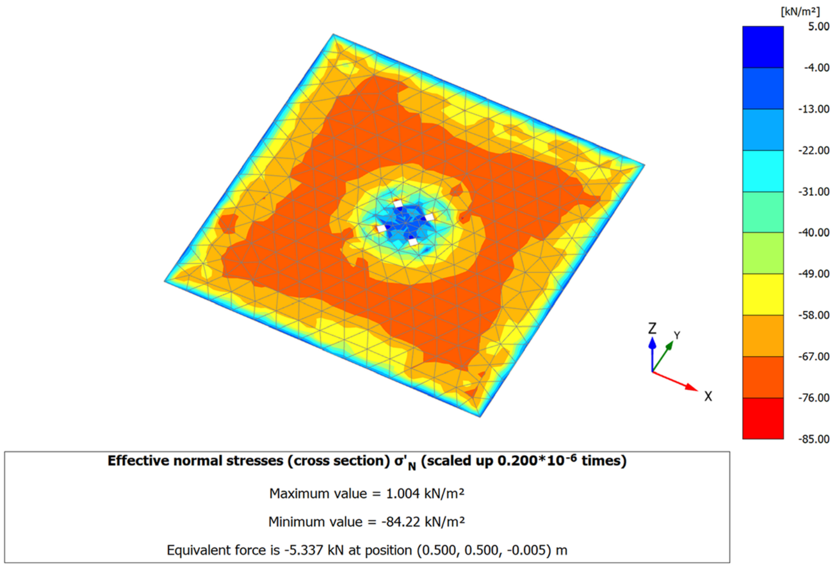


Fig. 9 *Contour map of the effective stress shared by the raft foundation in the case of 4 piles*

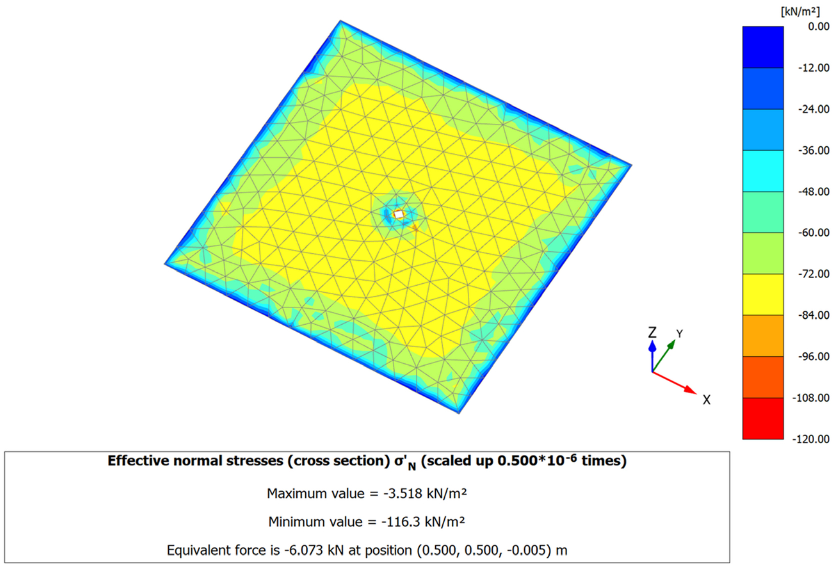


Fig. 10 *Contour map of the effective stress shared by the raft foundation in the case of a single pile*

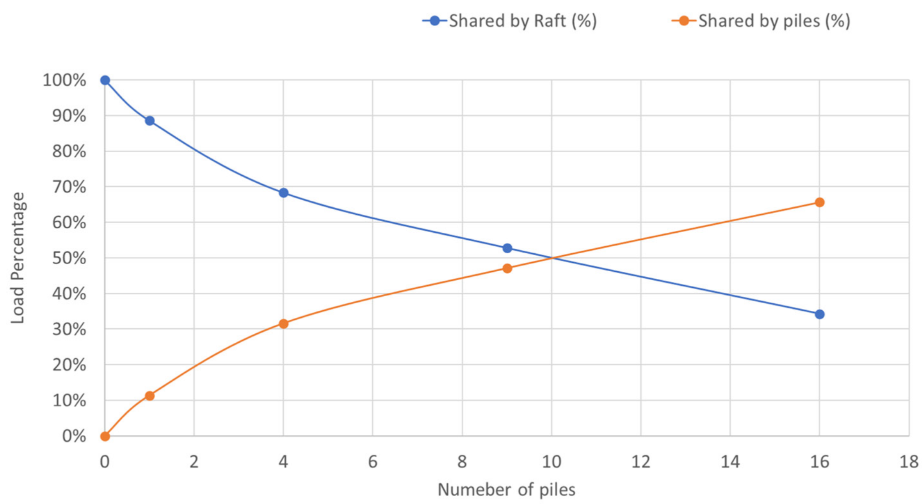


Fig. 11 *The percentage of load sharing between the raft and piles versus the number of piles*

5 CONCLUSIONS

This study has presented a comprehensive numerical investigation into the behavior of floating piled raft foundations in sandy soils using a calibrated three-dimensional finite element model. The analysis focused on load-sharing behavior, the settlement response, and stress distribution under vertical loading, with validation against empirical data from El-Garhy et al. (2013).

- The Reliability of the Model: The finite element model, which was validated with experimental load–settlement data, showed a high degree of predictive accuracy with a root mean square error (RMSE) of ~0.45 kN. This confirms its utility for evaluating raft–pile–soil interaction in similar geotechnical scenarios.

- Optimal Pile Count Identified: A configuration of 10 piles provided a balanced load-sharing ratio (approximately 50% raft, 50% piles), marking the transition point beyond which additional piles yielded diminishing returns. Increasing the pile count from 10 to 16 resulted in only a 3–5% further reduction in the settlement, which indicates that additional piles beyond this threshold are structurally inefficient and economically unjustified.

- Raft Remains Structurally Significant: Even with higher pile counts, the raft continued to contribute substantially to the vertical load resistance. For instance, in the 16-pile configuration, the raft still carried over 35% of the total load, thereby reinforcing the necessity to model the raft–soil interaction explicitly in the design.

- Trends in the Reduction of the Settlement: The inclusion of the piles significantly reduced the total settlement compared to the raft-only configuration. The settlement dropped from 26.5 mm (raft-only) to 11.2 mm in the 16-pile case. However, the rate of settlement improvement decreased notably after the 9-pile setup.

- Stress Distribution Confirmed Load Redistribution: Effective stress contours under the raft revealed a shift in the load transfer from highly localized stress in the single-pile case to a more uniform distribution in multi-pile configurations. This shift supports improved foundation performance in terms of reduced differential settlement and better stress diffusion.

Acknowledgments

The EU Next Generation EU funded this article through the Recovery and Resilience Plan for Slovakia under Project No. 09I03-03-V05-00005. Additionally, this work was supported by VEGA Grant No. 1/0597/25.

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