Mathematical Modelling for Sustainable Engineering
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Performance Assessment of Tower Crane Foundation Systems under Ultimate Loading Conditions

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Received: 10-05-2025 **Revised:** 11-14-2025 **Accepted:** 11-28-2025

Citation: M. Karabulut and S. Çevik, "Performance assessment of tower crane foundation systems under ultimate loading conditions," *Math. Model. Sustain. Eng.*, vol. 1, no. 2, pp. 73–81, 2025. https://doi.org/10.56578/mmse010201.

Abstract: Tower crane structural systems are widely used in large-scale construction projects, where foundation performance is critical to structural safety under ultimate loading conditions. In addition to satisfying ultimate bearing capacity, serviceability requirements—particularly total and differential settlements—must be rigorously addressed in foundation design. In this study, the performance of a tower crane foundation subjected to ultimate loads was evaluated using an integrated approach combining field testing, in situ monitoring, and finite element analysis. A tower crane foundation constructed for an industrial project was examined as a representative case. The subsurface profile comprised an uncontrolled fill layer overlying medium-dense sand, very stiff clay, and hard clay. Due to the high uncertainty associated with the fill material, plate load tests were conducted to characterize its deformation behavior. The test results were subsequently used in a back analysis with PLAXIS 2D to determine representative deformation parameters. The analysis indicated that the foundation dimensions recommended in the manufacturer's technical catalog were inadequate when settlement criteria were explicitly considered. Consequently, revised foundation dimensions of 8 m × 8 m were proposed. Finite element simulations were performed to evaluate the deformation response of the redesigned foundation under ultimate loading conditions. Field settlement measurements obtained at two monitoring points during operation exhibited close agreement with the numerical predictions. The study underscores the importance of integrating experimentally calibrated numerical analysis and field monitoring in the safety assessment of tower crane foundation systems, particularly for foundations resting on heterogeneous or uncontrolled soil deposits.

Keywords: Tower crane structural system; Foundation design; Settlement analysis; FEM; PLAXIS 2D; Plate load test; Bearing capacity; Field monitoring

1 Introduction

Tower crane structural systems are widely utilized, especially in the construction of high-rise buildings and industrial projects. The height and plan dimensions of tower crane structures vary depending on their lifting capacity and intended operational conditions. From a geotechnical perspective, in addition to ensuring the structural bearing load capacity and settlement conditions in the foundation design, distinct settlement criteria must also be satisfied. Construction of foundations for tower crane structural systems typically relies heavily on the catalogs of manufacturing companies. However, these catalogs generally determine foundation dimensions by calculating the stresses that occur in the foundation soil due to the capacity of the tower crane structure. Additionally, information on bearing capacity, settlement, and distinct settlement calculations is not included. If collapses exceed the permitted limits, serious accidents may occur that may lead to loss of life and property. Considering this situation, it becomes evident that structural and geotechnical evaluation is crucial in the design of tower crane foundations.

Various studies related to tower crane structures can be found in the literature. Numerous studies have investigated the safety of tower crane structural systems using a wide range of analytical and experimental approaches [1–5]. Ku et al. [4] utilized in-loop robotic tower crane structures as an innovative approach to improve construction and tower crane safety and efficiency. Sadeghi and Zhang [5] studied an innovative knowledge-based decision support system for safer tower crane structure operations and automatic safety risk assessment. In the research evaluating tower crane safety technologies, Ali et al. [1] presented tower crane structure accidents and death rates according to countries, highlighting the severity of safety risks associated with crane operations. Jiang et al. [2] conducted a stability analysis for lifting safety of the tower crane structure using a scale model based on digital twin technology.

Additionally, numerous studies have investigated the structural load-carrying capacity and location problems of tower crane structures [6–10]. Hussain et al. [6] utilized the digital twin method to predict the deteriorated lifting load capacity of aging tower cranes. Van Wittenberghe et al. [7] investigated the reliability of industrial overhead cranes with the structural health monitoring method. Dipu et al. [8] investigated cross-sectional models of the effective crane hook using the finite element method (FEM) and programming language. Qing et al. [9] presented an adaptive model for regression estimation of the crane load spectrum. Abdelmegid et al. [10] investigated an optimization model to solve the tower crane placement problem in construction sites. Borlea et al. [11] investigated the slip mode control of tower crane systems based on a discrete-time model. As an advantage of the control laws designed and implemented in the research, flexibility was used to validate the degrees of freedom offered by sliding-mode control, exhibiting a certain robustness. Precup et al. [12] studied the load position control of tower crane structural systems for proportional-integral fuzzy controllers using proportional-derivative learning rules. The role of soil parameters should be taken into account during the safety analysis of tower crane structures. Ézsiás et al. [13] investigated possible correlations between certain characteristics of crushed stone aggregates used in foundation soils.

Zhang et al. [14] conducted finite element analysis of bearing capacity, rotation, and flexural and torsion calculations for tower crane foundations under various loads using ANSYS and VB reinforcement software. The loads affecting the tower crane structure were categorized into four groups: its own weight, additional loads, special loads, and other loads. Wind and temperature were considered as special loads, while platform load and transportation load were defined as other loads. Based on the calculations, the foundation dimensions were determined to be 5 m × 5 m × 1.5 m. The analysis revealed that the wind load combination had the greatest impact on the required reinforcement area in the foundation. Despite the structural safety considerations made in tower crane foundation designs, Müllner and Meister [15] proposed that it is important to calculate settlements through structural-geotechnical interaction analysis for a safer and more economical foundation design. It was suggested that settlement calculations should be evaluated based on soil examination reports by considering various combinations. Several studies have examined finite element modeling of soils, nonlinear analyses and different soil material failure models [16–21].

The geotechnical evaluation of tower crane foundations has been limitedly studied in the literature. Therefore, this study presents a geotechnical evaluation of the tower crane foundation utilized during the construction of an industrial structure. Due to the presence of an uncontrolled fill layer in the soil profile, a series of plate load tests were conducted on-site to determine the elasticity modulus value of the fill layer. Using the data obtained, an analysis model was created with PLAXIS 2D software and back analysis was performed. Through this analysis, the soil deformation parameters of the uncontrolled fill layer were calibrated. Bearing capacity and settlement calculations were then carried out based on the obtained soil parameters.

2 Experimental Research

2.1 Soil Profile

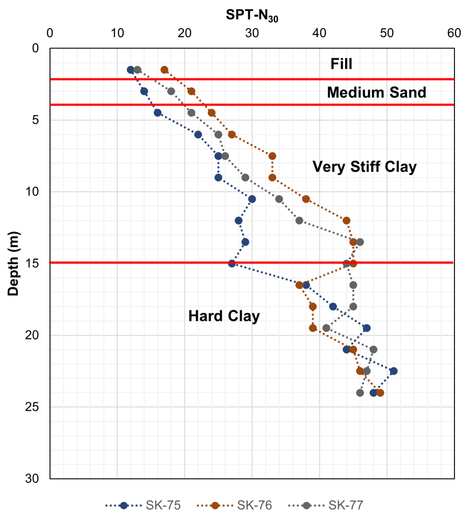


Figure 1. ASPT-N_{30} profile with depth

The soil profile at the location of the tower crane foundation, based on the nearest borehole, consists of the following layers from the surface downward: a 2 m-thick fill layer, beneath which there is a 2 m-thick layer of moderately dense sand, followed by an 11 m-thick layer of moderately stiff clay. At the bottom, there is a layer of stiff clay. The groundwater level is located at 10 m below the surface. The fill layer is primarily composed of construction waste, concrete and debris. It has been assessed that this layer may pose challenges related to settlement and bearing capacity issues in the foundation.

The variation of Standard Penetration Test (SPT-N_{30}) values with depth in the soil profile is illustrated in Figure 1. The average N_{30} values were determined to be 15 in the fill layer, 18 in the medium dense sand, 28 in the very stiff clay and 42 in the hard clay. For soil layers other than the fill layer, soil parameters were calculated according to formulas and correlations recommended in the literature.

2.2 Plate Load Test

A plate load test was conducted to determine the deformation parameters due to the uncontrolled nature of the fill layer. It is a commonly utilized field test for determining the bearing capacity of the soil, probable settlements of foundations and parameters such as the elasticity modulus and subgrade modulus [22]. The plate used in the experiment, which has become standardized in many countries, can be square or circular in shape. It is recommended that the selected plate should have a thickness of at least 25 mm, with sufficient rigidity to withstand the bending effects caused by loading [23]. During the experiment, plate settlements were observed for different load levels, and settlement-stress graphs were drawn. Using the slopes generated in the graph, soil elasticity modulus and subgrade modulus values were determined. Experiments were conducted at two selected points, designed to represent the limits of the tower crane foundation in the field, and stress-strain relationships were determined. The experimental setup is shown in Figure 2. A truck filled with granular material was used as the vertical load. The steel plate used had a diameter of 300 mm and a thickness of 30 mm. Vertical load increments were applied in the sequence 0–60–120–230–350–470–580 kN, followed by staged unloading to 0 kN, aiming to calculate the stress-strain values obtained from the field experiments using the PLAXIS 2D software. The results of the experiments conducted at both points and the stress-strain results calculated through back analysis are presented in Figure 3.

Figure 2. Plate load test setup

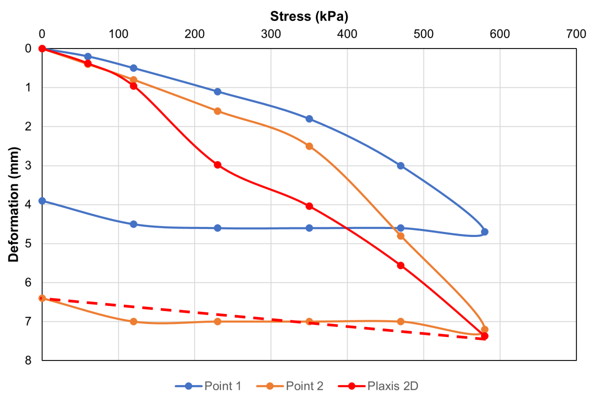


Figure 3. Comparison of the plate load test field data and back analysis result

2.3 Soil Parameters

The soil parameters of the medium dense sand, very stiff clay, and hard clay layers were determined based on field and laboratory test results as well as formulations and correlations recommended in the literature. For the fill layer, as there was no data available for determining strength parameters, the internal friction angle and cohesion values were conservatively determined. The elasticity modulus was determined through back analysis. The soil parameters are summarized in Table 1.

Table 1. Deformation and strength parameters of soil layers

Layer	Unit Weight, γ (kN/m^3)	Undrained Shear Strength, c_u (kPa)	Effective Cohesion c' (kPa)	Internal Friction Angle, ϕ' (°)	Elasticity Modulus E (MPa)
0.00–1.00 m Fill (Mohr–Coulomb, MC)	19	–	5	25	50
1.00–4.00 m Medium Sand (Hardening Soil, HS)	19	–	5	28	10
4.00–15.00 m Very Stiff Clay (HS)	19	50	–	–	21
>15.00 m Hard Clay (HS)	19	140	–	–	50

All soil parameters used in the numerical analyses were derived from the site investigation data and verified through widely accepted empirical correlations. Strength and basic stiffness properties of granular and transitional layers were obtained from SPT-N_{30}–based correlations, while cohesive layers were characterized by undrained shear strength results.

2.4 Tower Crane Foundation Design

The initial dimensions of the tower crane foundation were planned to be 6 m × 6 m in a square shape, considering the crane manufacturer's catalog. Subsequently, an analysis was conducted based on these dimensions, and the suitability of the application was checked. According to the manufacturer's catalog, the most unfavorable load conditions are 242 kPa on the front support and 115 kPa on the rear support of the crane. When calculations were made based on these dimensions, the maximum settlement was calculated as 8.1 cm, differential settlement as 6 cm, and angular rotation as β = 1/100. The calculated angular rotation value, which is less than 1/150 according to the Bjerrum criterion given in Table 2, suggests that differential settlement problems may occur in the foundation [24].

Table 2. Angular rotation limits for foundations [24]

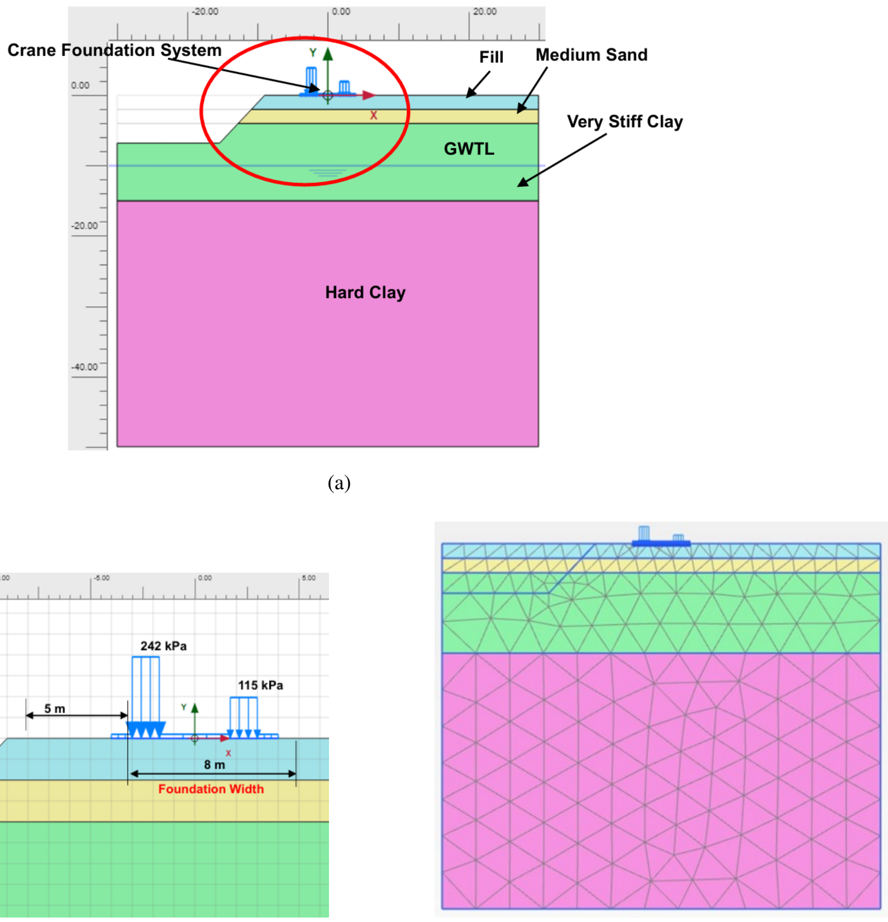
Category of Potential Damage	β_{max}
Safe limit for the flexible brick wall (L/H > 4)	1/150
Danger of structural damage to most buildings	1/150
Cracking of panel and brick walls	1/150
Visible tilting of high rigid buildings	1/250
First cracking of panel walls	1/300
Safe limit for no cracking of building	1/500
Danger to frames with diagonals	1/600

3 Finite Element Analysis

Novel development of the FEM, known as isogeometric FEM [25], allows for accurate description of complex geometries by means of Non-Uniform Rational B-Splines (NURBS) used as shape functions. However, the relatively simple geometry of the considered case allows for adequate description by means of classical FEM shape functions as well. Hence, the finite element model was developed using PLAXIS 2D, a widely adopted numerical analysis software for geotechnical applications. The geometry was discretized using a sufficiently fine mesh, in which the soil domain and structural elements were divided into triangular elements. The mesh density was increased in regions where high stress gradients were expected, particularly around the foundation boundaries and load application points. Mesh refinement was performed until no significant changes were observed in the results, ensuring mesh-independent solutions.

The analysis employed 15-node triangular elements, using quadratic shape functions to accurately capture stress and deformation distributions within the continuum. These higher-order elements provide improved numerical precision, especially for problems involving non-linear soil behavior. Full boundary conditions were assigned according to standard geotechnical modeling practice. The vertical boundaries were constrained in the horizontal direction while remaining free vertically, preventing lateral movement but allowing settlement. The bottom boundary was fixed in both horizontal and vertical directions to simulate a rigid base. Each node in the 15-node triangular elements possesses two degrees of freedom, corresponding to horizontal and vertical displacements. The overall model therefore comprises several thousand degrees of freedom, depending on mesh density.

The calculations were conducted using the updated Lagrangian formulation and an iterative Newton–Raphson scheme, which ensures stable convergence for nonlinear soil–structure interaction problems. PLAXIS 2D is widely used for obtaining displacement and similar response values, and it has been emphasized that its results are highly consistent with actual experimental and/or field measurement data [16, 26, 27]. Therefore, a two-dimensional analysis is considered sufficiently reliable and satisfactory. For these reasons, the present study was conducted using a two-dimensional model. The lateral boundaries were constrained with roller conditions, allowing vertical movement while preventing horizontal displacement, whereas the bottom boundary was fully fixed in both horizontal and vertical directions to represent the underlying stiff stratum.



(a)

(b)

(c)

Figure 4. Finite element model of the tower crane foundation system: (a) soil types; (b) loads and distances; (c) the finite element type used for the meshed soil domain

Within the soil profile, both the MC and HS models were used depending on the behavioral characteristics and data availability for each layer. The MC model was assigned to layers for which conventional parameter sets (c, φ, γ, E, and v) provided an adequate representation of global behavior, whereas the HS model was used for compressible cohesive units where stress-dependent stiffness could be reliably defined using E_{50}, E_{oed}, and E_{ur} values from laboratory data and validated empirical relationships. Elastic and stiffness moduli for MC layers were therefore determined either from SPT-based correlations (granular soils) or from oedometer and triaxial modulus interpretations (cohesive soils), while HS model parameters were established using laboratory-derived E_{50}, E_{oed}, and E_{ur} values, with E_{ur} taken as 3–5 times E_{50} following standard PLAXIS recommendations. This combined modeling approach allowed each layer in the profile to be represented using the most appropriate constitutive model based on its geological characteristics and available test data, resulting in a more realistic description of soil behavior in the numerical analyses.

Due to the initial dimensions of the foundation from the manufacturer's catalog being on the unsafe side, new foundation dimensions were selected as 8 m × 8 m. A finite element model of the tower crane foundation system was then created using the PLAXIS 2D software, as shown in Figure 4. The tower crane dimensions and loads are illustrated in the figure. Considering the soil parameters detailed in the previous section, the vertical displacement graph of the foundation is shown in Figure 5, based on the analysis conducted. According to the analysis results, the total settlement is calculated as 6.8 cm and the differential settlement is 3.0 cm. The angular rotation is β = 3/800 = 1/266, which is less than 1/150, thus satisfying the limit given in the literature [24]. Triangular finite elements were used in this study. In general, as recommended in the literature, the mesh density gradually transitions from coarser to finer regions; the element size is approximately 5 m in the finer zones, while it is about 10 m in the coarser regions.

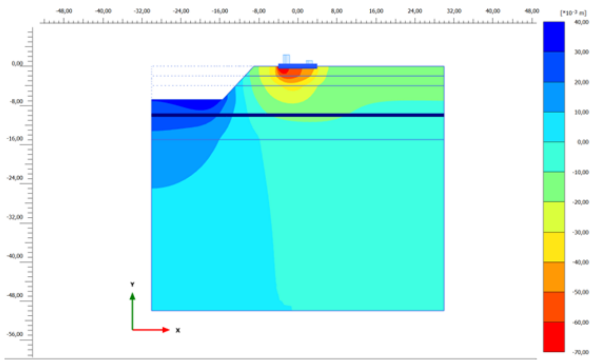


Figure 5. Foundation settlement results

Figure 5 presents the total vertical displacements u_y (scaled by a factor of 20). The analysis indicates a maximum displacement of 0.03721 m occurring at Element 192 (Node 624), while the minimum displacement, –0.06788 m, is observed at Element 35 (Node 1371).

4 Field Observations

To monitor the progression of settlements during the operation of the tower crane structural system, two measurement points were strategically installed at critical locations around the foundation. The tower crane, its foundation, and the corresponding measurement points are presented in Figure 6. Settlement readings were recorded daily during the first ten days following the construction of the crane foundation, after which measurements were taken at regular intervals for the remainder of the observation period. In total, settlement monitoring was carried out over a duration of 32 days.

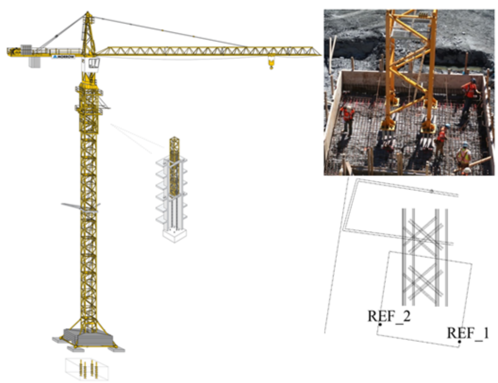


Figure 6. Tower crane structural system, foundation, and settlement observation points [28, 29]

The maximum settlement was observed at the front side of the foundation—where the applied loads are most significant—with a recorded value of 64 mm, while the rear side of the foundation experienced a comparatively smaller settlement of 45 mm. The measured settlement values obtained from field observations were subsequently compared with those computed through the finite element analysis performed using PLAXIS 2D. A graphical comparison of these results is provided in Figure 7. As shown in the figure, the field measurements exhibit a high degree of agreement with the numerical predictions generated by PLAXIS 2D. This strong correlation between measured and calculated settlements confirms the reliability of the finite element model and supports the validity of the overall design approach.

The comparison between the measured field settlements and those obtained from the numerical model was evaluated both graphically and quantitatively to ensure a reliable assessment of model performance. The settlement comparison plot presented in the study provides a direct visual interpretation of the agreement between observations and simulations, while the numerical evaluation was enhanced by calculating the absolute and percentage differences between the measured and computed values. These differences fall within a reasonable range considering the natural variability of soil stiffness, the layered structure of the subsurface, and the stress-dependent behavior of the materials. The remaining discrepancies are primarily attributed to local heterogeneities within the soil profile, construction-stage effects not fully represented in the model, and the inherent simplifications associated with the constitutive models used in the analyses.

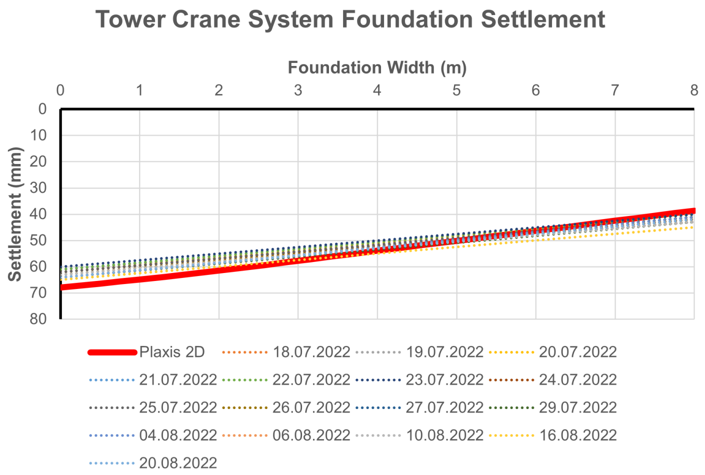


Figure 7. Settlement observations

5 Conclusions

In this study, a geotechnical design evaluation of tower crane foundations was conducted, focusing on a case analysis of the foundation used in the construction of an industrial structure. The soil profile consists of fill, medium-dense sand, very stiff clay, and hard clay layers. Due to the uncontrolled nature of the fill layer, the possibility of settlement problems was assessed. Therefore, to determine the deformation parameters of the fill layer, plate load tests were conducted at three points within the boundaries of the tower crane foundation. Using the field data obtained, a back analysis was performed with PLAXIS 2D software to determine the deformation parameters of the fill layer. The initially planned implementation involved applying the foundation dimensions recommended in the tower crane manufacturer's catalog, which were 6 m × 6 m. In this type of catalog, the foundation dimensions are determined by calculating the stresses that occur in the foundation soil due to the tower crane's capacity, but calculations for bearing capacity, settlement, and different settlement conditions are not typically included. According to the calculations, it was observed that the conditions for settlement and differential settlement were not satisfied for these dimensions.

The foundation dimensions were chosen as 8 m × 8 m, and a finite element analysis was conducted using PLAXIS 2D software. The maximum loads acting on the supports of the tower crane were considered as 242 kPa for the front support and 115 kPa for the rear support, based on the manufacturer's catalog. According to the analysis results, the total settlement was calculated as 6.8 cm, and the differential settlement was 3.0 cm. The angular rotation β = 3/800 = 1/266, which is less than 1/150. To monitor deformations during the operation of the tower crane system, measurement points were established at two locations and settlement measurements were taken at specific intervals over a period of 32 days. The maximum settlements observed in the foundation were measured as 64 mm at the front side and 45 mm at the rear side. It was observed that the settlement readings in the field were on a similar order of magnitude to the settlement values calculated using the FEM. The following conclusions were drawn regarding the structural and geotechnical evaluation of tower crane system foundations:

- Settlement and differential settlement calculations, which are often not present in tower crane catalogs, become crucial during the operation of the crane in practical applications.
- Foundations of tower cranes to be used in the construction process should be dimensioned according to the local soil profile and parameters.
- Evaluating theoretical settlement values along with field data, if available, can help prevent potential adverse effects arising from differential settlement.
- It has been determined that the static nonlinear settlement results of the finite element tower crane foundation model are in good agreement with the experimental results obtained from the field. Therefore, it is suggested that the ground settlement values of the tower crane foundation can be predicted by the two-dimensional finite element model.
- In further studies, it is recommended that the soil be modeled in three dimensions and compared with the two-dimensional model and field settlement data.

Author Contributions

Conceptualization, M.K. and S.Ç.; methodology, M.K.; software, M.K. and S.Ç.; validation, M.K. and S.Ç.; formal analysis, S.Ç.; investigation, M.K. and S.Ç.; resources, M.K.; data curation, S.Ç.; writing—original draft preparation, M.K. and S.Ç.; writing—review and editing, M.K..; visualization, M.K.; supervision, M.K.; project administration, M.K.; funding acquisition, M.K. All authors have read and agreed to the published version of the manuscript.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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