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Analysis of Vertical Bearing Characteristics of Pile Foundation Using Load Transfer Method

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Abstract: The vertical bearing and settlement characteristics of pile foundation are key issues in pile foundation design. In order to study the vertical loading characteristics of bored piles under complex stratigraphic conditions, this paper takes a bridge abutment engineering pile as the research object, and uses the load transfer method to systematically calculate and analyze the vertical bearing performance and settlement law of a single pile based on the field geological survey data. According to the engineering properties of different soil layers in which the pile body is located, the numerical solution method of the measured curve is selected to establish the transfer function relationship between the pile side friction resistance and displacement, and the pile body is discretely divided into several calculation units, and the axial force distribution, the change of pile side friction resistance and the settlement of the pile roof are calculated step by step through the displacement coordination conditions and the static balance equation. Under the assumption of different pile end displacements, the load-settlement relationship curve of a single pile is obtained. The calculation results show that with the increase of load, the side friction resistance of the pile gradually develops and tends to the limit, and the axial force of the pile body shows obvious attenuation characteristics along the depth. The established load-settlement curve can better reflect the vertical load deformation of a single pile. The research results can provide a reference for the design and bearing capacity evaluation of pile foundations under similar engineering conditions.

Keywords: Pile Foundation; Load Transfer Method; Vertical Bearing Performance; Settlement Calculation; Bored Piles; Pile Side Friction Resistance.

1. Introduction

Pile foundations are extensively applied in bridge engineering, high-rise buildings, and transportation infrastructure due to their high load-bearing capacity and suitability for complex geological conditions. The vertical bearing behavior and settlement characteristics of piles under axial loading play a decisive role in the safety, durability, and serviceability performance of superstructures. Excessive pile settlement may lead to uneven deformation, structural damage, and long-term serviceability problems, making accurate prediction of pile load–settlement behavior a fundamental issue in geotechnical engineering design [1,2].

Over the past several decades, various analytical, numerical, and empirical approaches have been proposed to evaluate the axial response of pile foundations. These methods mainly include elastic continuum theory, shear displacement methods, load transfer methods, and finite element analysis [3–5]. Elastic theory-based approaches consider soil as a continuous medium and are capable of accounting for pile–soil interaction; however, they typically assume linear elastic soil behavior, which is inconsistent with the inherently nonlinear and stress-dependent characteristics of real soils [6]. Finite element methods, although powerful in modeling complex constitutive relationships and boundary conditions, require extensive soil parameter calibration and significant computational effort, which often limits their application in routine engineering practice [7].

Among the available approaches, the load transfer method has gained widespread acceptance due to its clear physical interpretation, relatively simple formulation, and strong adaptability to layered soil conditions. Originally developed by Seed and Reese and further improved by Coyle, Reese, and Vijayvergiya, this method models the pile as a series of discrete elements connected to surrounding soil through nonlinear springs representing shaft resistance and base resistance [8–10]. The use of load–displacement transfer functions, commonly referred to as t–z curves for shaft resistance and q–z curves for pile tip resistance, enables the load transfer method to effectively capture the nonlinear mobilization process of pile–soil interaction [11].

Nevertheless, the reliability of the load transfer method largely depends on the appropriate selection of transfer functions. In practical engineering projects involving complex stratified soils, such as fill soil, collapsible loess, and clay layers influenced by groundwater conditions, the load–displacement relationship often exhibits strong nonlinearity and variability. Simplified analytical transfer functions may fail to accurately represent the actual pile behavior under such conditions [12]. Therefore, numerical solution schemes based on experimentally measured or empirically derived transfer curves are increasingly adopted to improve prediction accuracy.

In this study, a drilled cast-in-place concrete pile used in a bridge foundation project is selected as a case study. Based on detailed site investigation data, the pile penetrates multiple soil layers, including fill soil, loess, and silty clay. The load transfer method combined with a numerical displacement coordination approach is employed to investigate the vertical bearing capacity, axial force distribution, shaft resistance mobilization, and settlement characteristics of the single pile under different pile toe displacement conditions. The results provide a comprehensive understanding of the pile load transfer mechanism and offer valuable reference for the design and evaluation of pile foundations in similar geological environments.Comprehensive Analysis of Seismic Design Methods and Mitigation Strategies in Cable-Stayed Bridges

1.1. Overview of Methods for Vertical Bearing Capacity and Settlement Analysis of Pile Foundations

Pile foundations are extensively used in engineering practice to transfer structural loads to deeper and more competent soil layers. The vertical bearing capacity and settlement behavior of piles under axial loading are critical factors governing the safety and serviceability of foundation systems. Accurate prediction of pile settlement and load transfer mechanisms has therefore remained a central topic in geotechnical engineering research.

Over the past decades, a variety of analytical and numerical methods have been developed to evaluate the vertical response of pile foundations. These methods differ mainly in their treatment of pile–soil interaction, soil continuity, and material nonlinearity. Among the commonly adopted approaches are the load transfer method, the shear displacement method, and the elastic continuum method. Each method is based on distinct theoretical assumptions and is suitable for different engineering conditions and levels of analysis accuracy.

However, this method assumes that soil deformation at a given depth is governed only by local shaft resistance, neglecting the continuity of soil deformation [16]. Consequently, it is primarily applicable to single-pile analysis. Despite this limitation, the load transfer method remains a fundamental and efficient tool for evaluating vertical bearing capacity and settlement behavior of pile foundations.

1.2. Load Transfer Method

The load transfer method discretizes the pile into a series of elements and represents pile–soil interaction through nonlinear springs, allowing explicit consideration of soil stratification and nonlinear resistance mobilization. The shear displacement method emphasizes the role of soil shear deformation along the pile shaft and assumes perfect bonding between pile and soil. In contrast, the elastic continuum method models the soil as a continuous elastic medium and evaluates pile settlement through displacement compatibility between the pile and the surrounding soil.

A clear understanding of the theoretical background, assumptions, and applicability of these methods is essential for selecting an appropriate analysis approach in practical pile foundation design. Therefore, this section presents a brief introduction to the fundamental principles of the major methods used for vertical bearing capacity and settlement analysis of pile foundations. The load transfer method is one of the earliest and most widely used approaches for analyzing the vertical load–settlement behavior of pile foundations [13,14]. In this method, the pile is discretized into a series of axial elements, and the interaction between the pile and surrounding soil is represented by nonlinear springs distributed along the pile shaft and at the pile base. These springs characterize the load–displacement relationships of shaft resistance (t–z curves) and end bearing (q–z curves).By enforcing force equilibrium and displacement compatibility for each pile segment, the axial force distribution, mobilization of shaft resistance, and pile settlement can be determined through an incremental calculation procedure [15]. The load transfer method explicitly considers pile compressibility, soil stratification, and nonlinear pile–soil interaction, making it particularly suitable for practical engineering applications involving layered soils.

2. Analysis Methods for Vertical Behavior of Pile Foundations

2.1. Shear Displacement Method

The shear displacement method is based on the assumption that pile settlement is mainly controlled by the shear deformation of the surrounding soil along the pile shaft [17]. In this approach, the pile and soil are assumed to deform compatibly without relative slip at the pile–soil interface, and the pile displacement is directly related to the shear strain developed in the adjacent soil.

Load transfer along the pile shaft is described through shear stress–displacement relationships derived from soil deformation characteristics, and nonlinear functions are often introduced to represent the progressive mobilization of shaft resistance and base resistance [18]. Compared with the load transfer method, greater emphasis is placed on soil deformation mechanisms rather than interface slip behavior.

The primary limitation of the shear displacement method lies in the assumption of perfect bonding between pile and soil, which may not be realistic under large load levels when interface yielding occurs. Therefore, this method is generally applicable to cases involving relatively small settlements and strong pile–soil interaction.

2.1.1. Elastic Continuum Method

The elastic continuum method treats the soil surrounding the pile as a continuous, homogeneous, and isotropic elastic medium [19]. Based on elastic theory, soil displacements are calculated using analytical solutions for a semi-infinite elastic body subjected to internal loads, while the pile is divided into multiple segments undergoing elastic compression.

By enforcing displacement compatibility between the pile and surrounding soil, equilibrium equations are established to determine pile settlement and axial force distribution [20]. This method explicitly considers soil continuity and provides a rigorous theoretical framework for analyzing pile–soil interaction, which can be extended from single-pile behavior to pile group response.

Nevertheless, the elastic continuum method is inherently limited by its linear elastic assumptions. Real soils exhibit nonlinear and stress-dependent behavior that cannot be fully captured by elastic theory [21]. Despite these limitations, the method remains valuable for theoretical studies and as a benchmark for validating more advanced numerical models.

2.1.2. Numerical Implementation of the Load Transfer Method

The numerical implementation of the load transfer method is commonly carried out using an incremental–iterative procedure, in which the pile is discretized into a finite number of segments along its length [22]. Each pile segment is assumed to behave elastically, while the interaction between the pile and surrounding soil is represented by nonlinear load–displacement relationships defined at the pile–soil interface.

In a typical numerical procedure, an assumed pile toe displacement is first specified as the control parameter. The corresponding base resistance is then calculated based on the pile tip load–displacement relationship. Starting from the pile toe and proceeding upward segment by segment, equilibrium conditions are enforced to determine the axial force at each segment, while the mobilized shaft resistance is obtained from the prescribed *t–z* curves according to the local displacement level [23]. The elastic compression of each pile segment is subsequently calculated, allowing the

displacement profile along the pile shaft to be updated.

Displacement compatibility is checked at each calculation step to ensure consistency between the assumed and computed displacements. The procedure is repeated iteratively until convergence is achieved for the entire pile. By incrementally increasing the assumed pile toe displacement, the load–settlement relationship at the pile head can be established, providing a direct basis for evaluating pile bearing capacity and settlement behavior [24].

This numerical approach enables effective consideration of soil stratification, nonlinear pile–soil interaction, and pile compressibility. Due to its clear physical meaning and computational efficiency, the method is well suited for implementation using spreadsheet tools or simple numerical programs, making it particularly attractive for practical engineering analysis and design applications.

2.2. Engineering Background and Pile–Soil Conditions

2.2.1. Pile Geometry and Material Properties

The pile analyzed in this study is a drilled cast-in-place concrete pile constructed for a bridge abutment foundation. The pile is designed to sustain vertical loads transferred from the superstructure and to limit settlement under service conditions. A slurry-supported drilling method is adopted during construction to ensure borehole stability.

The total pile length is 16 m, and the pile diameter is 0.8 m. The pile is cast using C40 concrete, and the elastic modulus of the pile material is taken as 29,500 MPa. The pile is assumed to behave elastically under the applied vertical loads. These geometric and material parameters are used consistently throughout the numerical analysis to evaluate axial force distribution and pile deformation.

The pile toe is embedded in a competent soil layer, allowing both shaft resistance and end bearing resistance to contribute to the vertical load-carrying capacity. The pile is discretized into multiple segments along its length to facilitate numerical implementation of the load transfer method and to accurately represent variations in pile–soil interaction behavior.

2.2.2. Subsurface Stratification and Soil Properties

According to the site geotechnical investigation, the subsurface profile consists of three primary soil layers along the pile length: fill soil, loess, and silty clay. The uppermost fill soil layer has a thickness of approximately 4 m and is characterized by relatively high stiffness and shear strength. Beneath this layer lies an 8 m thick loess deposit, which exhibits sensitivity to moisture content and potential collapsibility.

The pile toe is located within the silty clay layer, which provides relatively stable mechanical properties and contributes to the pile's end bearing resistance. Laboratory testing and in-situ investigations are used to determine the allowable bearing capacity and standard shaft resistance values for each soil layer. These parameters vary significantly with depth, leading to nonuniform mobilization of shaft resistance along the pile shaft.

To capture the influence of soil stratification, layer-specific mechanical properties are adopted in the analysis. This approach allows the effects of soil heterogeneity on pile settlement and axial force distribution to be explicitly considered, forming a realistic basis for the subsequent load transfer analysis.

2.3. Load–Displacement Relationship and Transfer Functions

The load–displacement relationship between the pile and surrounding soil plays a critical role in the load transfer method. In this study, nonlinear transfer functions are employed to describe the relationship between shaft resistance and relative displacement along the pile shaft, as well as between base resistance and pile toe displacement.

Due to the complexity of the soil conditions and the nonlinear mechanical behavior of the pile–soil interface, analytical expressions are not sufficient to accurately represent the load–displacement relationship. Therefore, a numerical approach based on experimentally obtained or empirically derived curves is adopted. For each soil layer, the shaft resistance–displacement relationship is defined using discrete data points, which are subsequently interpolated during the numerical calculation.

The load–displacement transfer functions for fill soil, loess, and silty clay are summarized in Table 2 and illustrated in Figure 2. These curves reflect the progressive mobilization of shaft resistance with increasing displacement and clearly demonstrate the differences in mechanical behavior among the soil layers. The fill soil exhibits relatively rapid mobilization of shaft resistance, whereas the loess and silty clay layers show more gradual development and post-peak softening behavior.

By incorporating layer-specific transfer functions into the numerical procedure, the nonlinear interaction between the pile and surrounding soil can be realistically simulated. This approach enables accurate prediction of axial force distribution, shaft resistance mobilization, and settlement behavior under different loading conditions, providing a reliable basis for evaluating the vertical bearing performance of the pile foundation.

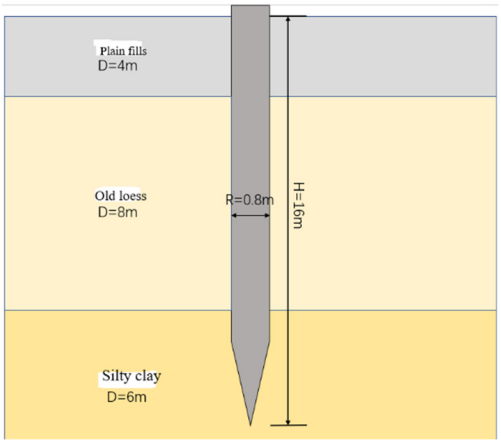

Fig 1. Relative position of pile body and soil layer

Table 1. Table Mechanical properties of each soil layer

Soil layer	layer thickness (m)	The bearing capacity is allowed to be worth fak (KPa)	Reaction coefficient Kb (MPa/m)	The standard value of friction resistance τf (KPa)
Plain fills	4	400		300
Old loess	8	180		210
Silty clay	6	180	240	100

3. Calculation Process

Because the pile crosses the complex soil layer, the loess layer has collapsibility, and the properties of the soil layer are greatly affected by groundwater, the transfer function relationship of the soil layer is complex, and here we use the numerical solution method. The transfer function relationship of various soil layers is as follows:

Table 2. Pile side transfer function

Soil layer category	Plain fills										
s/mm	0	0.25	0.50	0.75	1.00	1.25	1.50	1.75	2.00	2.25	2.50
τ/KPa	0	55	100	130	150	180	220	255	280	310	315
Soil layer category	Old loess										
s/mm	0	0.5	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00
τ/KPa	0	40	65	120	160	190	220	235	240	230	220
Soil layer category	Silty clay										
s/mm	0	0.5	1.00	1.50	2.00	2.50	3.00	3.50	4.00	4.50	5.00
τ/KPa	0	10	17	25	40	56	66	80	105	110	100



Fig 2. Curve of the transmission function of the side friction resistance of the pile

2.From the above engineering summary, it can be seen that the pile length L=16m, the diameter R=0.8m, the elastic modulus EP=29500, the settlement characteristics of the pile are calculated by the load transfer method, and the pile is divided into 10 units, and the length of each unit is $\Delta L = L/n = 1.6\text{m}$. The calculation model is shown in Figure 3:

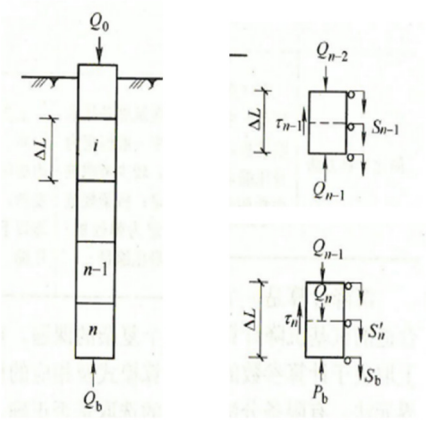

Fig 3. Calculation model of displacement coordination method

3.Suppose the displacement of the bottom surface of element 10 at the pile end $S_{b3} = 1.5mm$ (i.e., pile end displacement). The pile end resistance Pb (that is, the axial force of the pile at the pile end) caused by this displacement is calculated as follows:

$$P_b = K_b A_b S_b = 1.5 \times 240 \times 0.5024 = 180.9557KN$$

In the formula K_b, A_b ——The foundation reaction coefficient and pile cross-sectional area at the pile end, $K_b = \frac{240Mpa}{m}$, $A_b = 0.5024mm^2$.

4.Suppose the displacement at the cross-section of the midpoint of the pile in unit 10 $S'_n = 1.511mm$,Then the corresponding is obtained from the measured transfer function curve$S'_n = 1.511mm$ the side friction resistance of the pile is$\tau_{10} = 25kpa$

5.Then the axial force at the top surface of the 10th unitQ_{n-1}

$$Q_{n-1} = Q_b + \tau_{10} u \Delta L = 281.4867KN$$

6.Find the displacement of the pile at the center section of the pile in unit 10: $S_n = S_b + \Delta$,where Δ is the elastic compression of the pile in the second half of the 10th unit, that is

$$Q_n = \frac{1}{2}(Q_b + Q_{n-1}) = 231.22KN$$

$$\Delta = \frac{\Delta L}{2} * \frac{1}{A_p E_p} * \frac{Q_b + Q_n}{2} = 0.011mm$$

$$S_n = \Delta + S_{b3} = 1.511mm$$

7. Check whether it is true $S_n = S'_n$,Unit 10 $S_n = S'_n = 1.511mm$. getQ_b, Q_9, S_{10}, τ_{10}

Table 3. $S_b = 1.5mm$Axial force and pile side friction resistance of each unit

Pile Unit/(n)	Q/(KN)	S/(mm)	τ/(kpa)	z/(m)
0	6074.24	2.50	0	0
1	4867.87	2.50	300.00	1.6
2	3720.01	2.23	285.45	3.2
3	2650.20	2.01	266.04	4.8
4	2058.27	1.85	147.20	6.4
5	1516.53	1.73	134.72	8.0
6	999.24	1.64	128.64	9.6
7	491.60	1.58	126.24	12.2
8	385.03	1.55	26.50	13.8
9	281.49	1.53	25.75	15.4
10	180.96	1.51	25.00	16.0

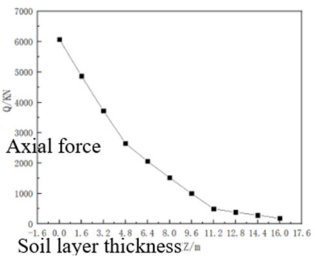

Fig 4. $S_{b=1.5}$ element axial force

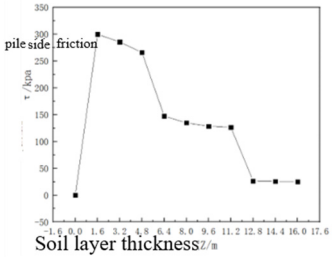

Fig 5. $S_{b=1.5}$ pile side friction resistance

8.Calculate the other elements according to the above steps, and move them up one by one until the first unit of the pile top, and the S_b pile top load P_0 and pile top settlement S_0 corresponding to the displacement of the pile end can be obtained.

9.Assume the displacement of the unit at the end of the pile $S_{b1} = 0.5$; $S_{b2} = 1.0$; $S_{b3} = 1.5$; $S_{b4} = 2.0$; $S_{b5} = 2.5$; $S_{b6} = 3.0$, The above 3~8 steps are calculated separately:

1) When the element is displaced at the end of the pile $S_{b1} = 0.5mm$, the calculation knot is as follows:

Table 4. $S_{b1} = 0.5mm$ Axial force and pile side friction resistance of each unit

Pile Unit/(n)	Q/(KN)	S/(mm)	τ/(kpa)	z/(m)
0	2320.66	0.87	0	0
1	1830.07	0.87	122.00	1.6
2	1367.62	0.76	115.00	3.2
3	919.26	0.68	111.50	4.8
4	718.19	0.62	50.00	6.4
5	529.19	0.58	47.00	8.0
6	352.26	0.55	44.00	9.6
7	183.37	0.53	42.00	12.2
8	141.55	0.52	10.40	13.8
9	100.53	0.51	10.20	15.4
10	60.32	0.50	10.00	16.0

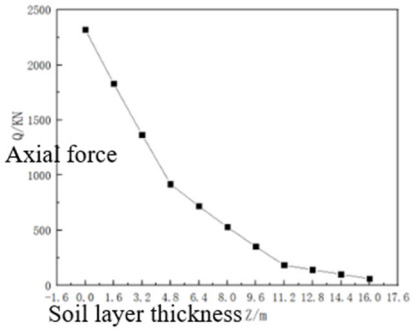

Fig 6. $S_{b1} = 0.5mm$ Axial force of the element

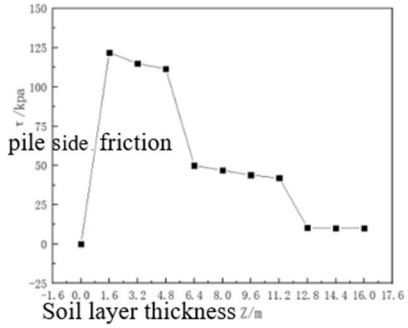

Fig 7. $S_{b1} = 0.5mm$ Pile side friction resistance

2) When the element is displaced at the end of the pile $S_{b2} = 1.0mm$, the calculation knot is as follows:

Table 5. $S_{b2} = 1.0mm$ Axial force and pile side friction resistance of each unit

Pile Unit/(n)	Q/(KN)	S/(mm)	τ/(kpa)	z/(m)
0	3956.90	1.60	0	0
1	3032.01	1.60	230.00	1.6
2	2211.68	1.43	204.00	3.2
3	1447.65	1.29	190.00	4.8
4	1150.07	1.21	74.00	6.4
5	866.98	1.14	70.40	8.0
6	593.53	1.09	68.00	9.6
7	326.52	1.05	66.40	12.2
8	257.36	1.03	17.20	13.8
9	189.00	1.02	17.00	15.4
10	120.64	1.01	17.00	16.0

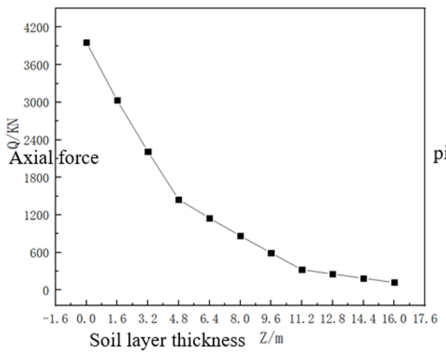

Fig 8. $S_{b2} = 1.0mm$ Axial force of the unit

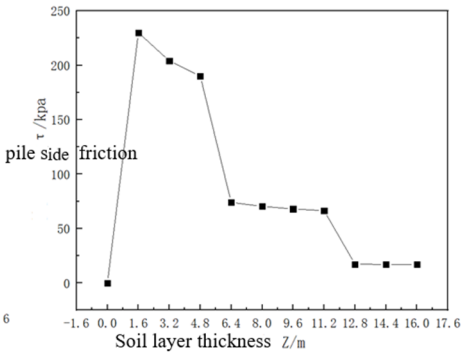

Fig 9. $S_{b2} = 1.0mm$ Pile side friction resistance

3.1. Axial Force Distribution along the Pile Shaft

The axial force distribution along the pile shaft provides fundamental insight into the load transfer mechanism between the pile and the surrounding soil. As shown in Fig. 7 and Fig. 9, the axial force decreases gradually with increasing depth, indicating that the applied load at the pile head is progressively transferred to the soil through shaft resistance.

At shallow depths, the axial force remains relatively high due to limited mobilization of shaft resistance. With increasing depth, the cumulative contribution of shaft resistance becomes more significant, resulting in a pronounced reduction in axial force. The rate of axial force attenuation varies across different soil layers, reflecting the influence of soil stratification on load transfer behavior.

In particular, layers with higher shaft resistance capacity exhibit steeper reductions in axial force, whereas softer layers show more gradual changes. These observations confirm that axial force distribution is strongly governed by the mechanical properties of the surrounding soil. Understanding this distribution is essential for evaluating load-sharing mechanisms and identifying critical sections along the pile shaft.

3.2. Mobilization of Shaft Resistance in Different Soil Layers

The mobilization of shaft resistance is closely related to the relative displacement between the pile and the surrounding soil. As illustrated in Fig. 8 and Fig. 10, shaft resistance increases progressively with displacement until reaching a peak or stable value.

In the upper fill soil layer, shaft resistance is mobilized rapidly at relatively small displacements, indicating a stiff response. In contrast, the loess layer exhibits a more gradual mobilization process, which can be attributed to its structural sensitivity and deformation characteristics. The silty clay layer shows comparatively stable mobilization behavior, contributing steadily to load transfer as displacement increases.

These results demonstrate that shaft resistance mobilization is highly dependent on soil type and stress–strain behavior. The use of layer-specific load–displacement relationships is therefore essential for accurately capturing pile–soil interaction. Failure to account for such differences may result in unrealistic estimation of settlement and bearing capacity.

3.3. Influence of Pile Toe Displacement on Load Transfer Behavior

To investigate the effect of pile toe displacement on load transfer behavior, multiple displacement levels are assumed and analyzed. The numerical results indicate that increasing pile toe displacement leads to enhanced mobilization of shaft resistance and increased contribution of end bearing resistance.

At smaller toe displacements, load transfer is primarily dominated by shaft resistance, and the pile response remains relatively stiff. As displacement increases, shaft resistance in some soil layers approaches its ultimate value, and additional load is increasingly transferred to the pile toe. This transition is clearly reflected in the axial force and shaft resistance distributions shown in Fig. 7-18.

The results highlight the nonlinear nature of pile–soil interaction and emphasize the importance of displacement-controlled analysis. Evaluating pile behavior under different displacement levels provides a comprehensive understanding of load-sharing mechanisms and failure progression.

3.4. Pile Settlement Characteristics

Pile settlement is obtained by combining elastic compression of the pile shaft with relative displacement at the pile–soil interface. The calculated settlement results indicate a nonlinear increase in settlement with applied load.

At lower load levels, settlement develops slowly, and the pile exhibits high stiffness. With increasing load, settlement accelerates due to progressive mobilization and partial degradation of shaft resistance, particularly within the loess layer. The influence of soil stratification on settlement behavior is evident from the variation in displacement profiles along the pile shaft.

These findings demonstrate that settlement behavior cannot be adequately described using linear assumptions. Accurate prediction requires consideration of nonlinear pile–soil interaction and realistic load–displacement relationships.

3.5. Load–Settlement Relationship at the Pile Head

Based on the numerical analysis results obtained for different pile toe displacements, the load–settlement relationship at the pile head is established, as shown in Fig. 19. The curve exhibits a clear nonlinear trend, reflecting progressive mobilization of shaft resistance and end bearing.

In the initial loading stage, the pile head load increases rapidly with small settlement, indicating high initial stiffness. As settlement increases, the slope of the curve decreases, corresponding to gradual exhaustion of shaft resistance and increased reliance on end bearing. This behavior is characteristic of friction piles in layered soils.

The load–settlement curve provides a direct basis for evaluating serviceability performance and estimating allowable bearing capacity based on settlement criteria.

3.6. Engineering Implications and Discussion

The numerical results demonstrate that the load transfer method is capable of capturing key features of vertical pile behavior, including nonlinear load transfer, soil stratification effects, and pile compressibility. The method provides clear insight into the contribution of different soil layers to load transfer and settlement.

From an engineering perspective, the results highlight the necessity of adopting realistic load–displacement transfer functions and accounting for soil heterogeneity in pile foundation design. Simplified methods that ignore these factors may underestimate settlement or misrepresent load-sharing mechanisms.

The findings of this study confirm that the load transfer method offers a reliable and efficient framework for evaluating the vertical bearing performance of pile foundations and can serve as a practical tool for engineering analysis and design.

4. Summary

Based on the load transfer analysis conducted for a single drilled cast-in-place pile in layered soil conditions, the vertical bearing behavior and settlement characteristics of the

pile are systematically investigated. The main conclusions drawn from this study are summarized as follows:

(1) The load transfer method effectively captures the nonlinear pile–soil interaction behavior.

By discretizing the pile into multiple segments and adopting layer-specific load–displacement transfer functions, the method successfully simulates the progressive mobilization of shaft resistance and end bearing resistance. The calculated axial force distributions and settlement responses clearly reflect the nonlinear characteristics of pile–soil interaction.

(2) Axial force decreases progressively with depth due to mobilization of shaft resistance.The numerical results indicate that the axial force along the pile shaft attenuates continuously with increasing depth, with the rate of reduction strongly influenced by soil stratification. Soil layers with higher shaft resistance capacity contribute more significantly to load transfer, while softer layers exhibit a more gradual reduction in axial force.

(3) Shaft resistance mobilization exhibits clear layer-dependent characteristics. Different soil layers show distinct mobilization behaviors. The fill soil layer mobilizes shaft resistance rapidly at small displacements, whereas the loess layer exhibits gradual mobilization and sensitivity to deformation. The silty clay layer provides relatively stable resistance, contributing steadily to the overall bearing capacity of the pile.

(4)Pile toe displacement plays a critical role in load-sharing mechanisms. With increasing pile toe displacement, shaft resistance approaches its ultimate value, and the contribution of end bearing resistance becomes increasingly significant. This transition highlights the importance of displacement-controlled analysis for accurately evaluating pile performance, particularly under higher load levels.

(5) Pile settlement exhibits a nonlinear load–settlement relationship. The load–settlement curve at the pile head demonstrates high initial stiffness at small settlements, followed by a gradual reduction in stiffness as shaft resistance becomes fully mobilized. This nonlinear response emphasizes that linear assumptions are insufficient for predicting pile settlement in layered soils.

(6)Engineering applicability of the load transfer method is confirmed. The results of this study demonstrate that the load transfer method provides a reliable and efficient tool for analyzing the vertical bearing performance of single piles in layered soil conditions. The method is particularly suitable for engineering applications where soil stratification and nonlinear pile–soil interaction must be considered.

In summary, the load transfer method offers clear physical interpretation, computational efficiency, and satisfactory accuracy for settlement analysis and bearing capacity evaluation of pile foundations. The findings of this study can provide useful reference for the design and analysis of pile foundations in similar geological conditions.

References

[1] Poulos, H. G., & Davis, E. H. (1980). Pile Foundation Analysis and Design. John Wiley & Sons.

[2] Tomlinson, M. J., & Woodward, J. (2015). Pile Design and Construction Practice. CRC Press.

[3] Randolph, M. F., & Wroth, C. P. (1978). Analysis of deformation of vertically loaded piles. Journal of the Geotechnical Engineering Division, ASCE, 104(12), 1465–1488.

[4] Cooke, R. W. (1974). The settlement of friction pile foundations. Géotechnique, 24(1), 23–43.

[5] Poulos, H. G. (1989). Pile behavior—Theory and application. Géotechnique, 39(3), 365–415.

[6] Mindlin, R. D. (1936). Force at a point in the interior of a semi-infinite solid. Physics, 7(5), 195–202.

[7] Potts, D. M., & Zdravković, L. (1999). Finite Element Analysis in Geotechnical Engineering. Thomas Telford.

[8] Seed, H. B., & Reese, L. C. (1957). The action of soft clay along friction piles. Transactions of ASCE, 122, 731–754.

[9] Coyle, H. M., & Reese, L. C. (1966). Load transfer for axially loaded piles in clay. Journal of Soil Mechanics and Foundations Division, ASCE, 92(2), 1–26.

[10] Vijayvergiya, V. N. (1977). Load–settlement characteristics of piles. Proceedings of Ports ’77 Conference, ASCE.

[11] Fellenius, B. H. (2019). Basics of Foundation Design. Electronic Edition.

[12] Zhang, Q., & Zhang, Z. (2012). Load transfer analysis of piles in layered soils. Soils and Foundations, 52(5), 875–885.

[13] Seed, H. B., & Reese, L. C. (1957). The action of soft clay along friction piles. Transactions of the ASCE, 122, 731–754.

[14] Coyle, H. M., & Reese, L. C. (1966). Load transfer for axially loaded piles in clay. Journal of the Soil Mechanics and Foundations Division, ASCE, 92(2), 1–26.

[15] Vijayvergiya, V. N. (1977). Load–settlement characteristics of piles. Proceedings of Ports ’77 Conference, ASCE.

[16] Poulos, H. G., & Davis, E. H. (1980). Pile Foundation Analysis and Design. John Wiley & Sons.

[17] Cooke, R. W. (1974). The settlement of friction pile foundations. Géotechnique, 24(1), 23–43.

[18] Randolph, M. F., & Wroth, C. P. (1978). Analysis of deformation of vertically loaded piles. Journal of the Geotechnical Engineering Division, ASCE, 104(12), 1465–1488.

[19] Mindlin, R. D. (1936). Force at a point in the interior of a semi-infinite solid. Physics, 7(5), 195–202.

[20] Poulos, H. G. (1971). Behavior of laterally loaded piles: I—Single piles. Journal of the Soil Mechanics and Foundations Division, ASCE, 97(5), 711–731.

[21] Randolph, M. F. (2003). Science and empiricism in pile foundation design. Géotechnique, 53(10), 847–875.

[22] Fellenius, B. H. (1984). Analysis of results from pile load tests. Ground Engineering, 17(6), 18–26.

[23] Reese, L. C., & O’Neill, M. W. (1988). Drilled Shafts: Construction Procedures and Design Methods. FHWA.

[24] Poulos, H. G. (2001). Pile behaviour—Consequences of geological and construction imperfections. Géotechnique, 51(2), 95–117.