

Research on the Influence of Soil Discrete Characteristics on the Bearing Capacity of PHC Pipe Piles in Soft-Soil Areas

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Abstract: Alluvial-lacustrine soft soils commonly exhibit strong spatial heterogeneity. Large variability in soil mechanical parameters often creates considerable discrepancies between theoretical bearing capacity predictions and field static-load test results for Prestressed High-strength Concrete (PHC) pipe piles. This study investigates a practical engineering case located in an alluvial-lacustrine depression in Wuhan. Geotechnical laboratory tests and static cone penetration measurements were performed to obtain in-situ physico-mechanical soil parameters. Combined with data from destructive full-scale single-pile static-load tests, this paper analyzes how soil spatial variability affects single-pile bearing performance. The results demonstrate that silty-mucky clay is the primary stratum responsible for bearing-capacity deviations at this site. When the mechanical parameters of this layer drop to their measured minimum values, the ultimate single-pile bearing capacity decreases by 7.8 %. Direct adoption of standard shaft and tip resistance values yields theoretical predictions 10.1 % higher than measurements from destructive static-load tests. A low-value coupling-attenuation effect emerges when multiple overlying soil layers exhibit simultaneously poor geomechanical indexes, which substantially degrades the overall bearing capacity of the pile. This work can offer practical references for PHC pipe-pile design considering adverse effects induced by soil-parameter variability in alluvial-lacustrine soft-soil sites.

Keywords: Alluvial-Lacustrine Soft Soil; Soil Dispersion; PHC Pipe Pile; Single-Pile Static-Load Test

1. Introduction

Soft soils are fine-grained deposits with a natural void ratio $e \geq 1.0$ and natural water content $w >$ exceeding the liquid limit w_L . Typical properties include high compressibility, low shear strength, high sensitivity, low permeability and significant rheological deformation; under strong seismic excitation, such soils may also suffer seismic subsidence. Soft-soil deposits mainly consist of muck, mucky soil, peat and peaty soil. In China, they are widely distributed in coastal regions, alluvial plains along middle-lower river courses, and lacustrine-marsh zones. These deposits originate from cohesive soil and silt sediments formed under quiescent or slow-flowing water and consolidated over long geological periods. Driven by rapid urbanization, numerous infrastructure projects have been constructed on soft-soil sites. Soil water content, compression modulus and shear strength vary markedly between different boreholes within one site and also with depth in individual boreholes. Large-volume structures sustain uneven loads and impose strict settlement limits. With advantages of reliable prefabricated quality and limited construction-induced disturbance, Prestressed High-strength Concrete (PHC) static pipe piles have become a widely adopted foundation solution for soft-soil regions[1,2]. Current studies on PHC pipe piles still have two obvious deficiencies. Firstly, theoretical analyses usually treat pile-surrounding soils as homogeneous media and fail to quantify resistance reduction induced by discreteness of different soil layers. Accordingly, it is difficult to interpret the internal causes of bearing capacity calculation deviations from the perspective of soil-parameter uncertainty[3]. Secondly, many existing research conclusions are derived merely from laboratory test data. Closed-loop supporting datasets covering geotechnical investigation, laboratory

geotechnical tests, in-situ tests, field static-load tests and engineering rectification are rarely available. Practical comparison is insufficient, and the practicability of optimization measures is relatively poor[4]. Relying on complete field geotechnical data, static cone penetration tests and single-pile static-load test data collected from a PHC pipe-pile project in Wuhan, this paper analyzes differentiated influences of soil discreteness on pile-shaft resistance and piletip resistance. It illustrates the multi-layer-soil low-value superposition-coupling effect and its influence mechanism on pile bearing capacity, and puts forward integrated optimization countermeasures for investigation, design and construction.

2. Engineering Site and Test Data

2.1 Site Stratigraphic and Hydro Sedimentary Characteristics

The investigated project is located in a gentle alluvial-lacustrine depression in Wuhan. The shallow ground is artificially filled with cohesive soil, construction waste and humus materials. Seven strata are revealed by geological exploration, and the measured geotechnical index ranges of each stratum are shown in Table 1. Great differences exist in sedimentary age, particle composition and consolidation state among these strata. The

silty-mucky clay stratum is rich in organic matter with rheological properties and odour of putrefaction; locally it contains thin interbeds of silt and silty sand, and distributes continuously over the whole site.

The silty-mucky-clay stratum contains high content of organic matter and humus. According to simple field water-quality test results, groundwater at this site is slightly corrosive to concrete structures and steel reinforcement inside reinforced-concrete components. The special water-soil environment of alluvial-lacustrine soft soil brings potential durability risks to PHC high-strength concrete pipe piles: long-term action of organic matter and corrosive ions accelerates concrete carbonation and corrodes welds at pile-pile joints.

Perched water and deep confined water coexist at this site. Perched water accumulates in fill layers and fractures of shallow cohesive soils and is recharged by seasonal rainfall, with an annual water-level fluctuation of about 1.5 m. hosted in sand interlayers and the mediumcoarse-sand bearing stratum, and maintains a stable hydraulic head. Long-term groundwater immersion reduces the effective stress of soft soils continuously and further aggravates mechanical-parameter discreteness of silty-mucky clay.

Table 1. Geotechnical Test Data

Stratum No.	Soil description	Natural water content(%)	Compression modulus range (MPa)	Cohesion range(kPa)	Internal friction-angle range(°)
①	Miscellaneous fill	26.1~41.5	1.2~2.9	6.2~13.8	4.1~8.6
① _a	Plain fill	27.3~36.8	1.6~3.3	7.5~15.2	5.2~9.7
②	Plastic silty clay	24.6~30.2	4.8~6.5	16.3~23.5	11.2~16.8
③ ₁	Silty-mucky clay	40.7~52.4	2.1~4.2	5.1~9.3	2.8~6.4
③ ₂	Soft-plastic silty clay	29.5~37.1	4.1~5.9	12.6~19.7	8.5~13.6
④	Fine sand interbedded with silt	23.2~31.6	7.6~10.8	9.4~16.5	18.3~26.7
⑤	Medium-coarse sand	19.5~25.3	14.2~18.1	—	28.5~34.2

2.2 Statistical Results of Laboratory Geotechnical Tests and Static Cone Penetration Tests

Twenty-nine standard exploration boreholes are deployed on-site including ten control boreholes. Undisturbed soil samples are taken at intervals of 0.8-1.2 m. A total of 136 groups of consolidation and direct-shear laboratory geotechnical tests are completed. Meanwhile, eight static cone penetration test profiles are carried out to record cone-tip resistance and sleeve-friction resistance along depth. All

parameters are original statistical results from field measurement.

Obvious discreteness differences can be distinguished from Table 1. For stratum ③₁ silty-mucky clay, the difference between upper-limit and lower-limit values of water content and compression modulus nearly doubles, which constitutes the primary source of soil discreteness on-site. Stratum ④ fine sand interbedded with silt shows moderate-level parameter fluctuation caused by lenticular soil bodies. Stratum ⑤ medium-coarse sand has well-sorted particles

and stable mechanical performance with small-magnitude index variation. In-situ indexes obtained from static cone penetration tests can be used for quantitative evaluation of

pile-shaft and pile-tip resistance[5,6]. Measured sleeve-friction-resistance values for each stratum are summarized in Table 2.

Table 2. Measured Sleeve Friction Resistance of Each Stratum (kPa)

Stratum No.	Soil description	Minimum measured value	Average measured value	Maximum measured value
①	Miscellaneous fill	6	10	14
① _a	Plain fill	7	10	13
②	Plastic silty clay	15	20	25
③ ₁	Silty-mucky clay	6	10	13
③ ₂	Soft-plastic silty clay	14	18	22
④	Fine sand interbedded with silt	14	18	23
⑤	Medium-coarse sand	32	37	42

3. Pile-Foundation Design and Single-Pile Static-Load Test

3.1 Ultimate Vertical Bearing Capacity of Single Pile

Structures in this project bear large loads with strict settlement-control requirements. For instance, the clear-water tank is a large-area uniformly-loaded structure sensitive to differential settlement and other deformation anomalies. Closed-end PHC-500(100) prestressed pipe piles with C80-grade concrete are adopted for pile foundations. The designed pile length ranges from 27 m to 30 m. The pile tip is required to penetrate 2.0-3.5 m into stratum ⑤ medium-coarse-sand bearing layer, and the characteristic single-pile bearing capacity shall be no less than 2600 kN.

The formula for the characteristic vertical ultimate bearing capacity of a single pile is given below:

$$Q_{uk} = u \sum q_{sik} l_i + q_{pk} A_p \quad (1)$$

Where:

Q_{uk} —ultimate vertical bearing capacity of single pile, kN;

u —perimeter of pile shaft, m;

l_i —thickness of the i -th soil layer, m;

q_{sik} —ultimate shaft resistance of the i -th soil layer, kPa;

q_{pk} — ultimate tip resistance at pile tip, kPa;

A_p — cross-sectional area of pile tip, m².

3.2 Technical Principle of Prestressed Concrete Pipe Piles

Prestressed concrete pipe piles are factory

prefabricated reinforced-concrete structural members, which are mainly divided into Prestressed High-strength Concrete (PHC) pipe piles and Prestressed Concrete (PC) pipe piles. Benefiting from high strength and good durability, PHC pipe piles are widely used in soft-soil-region engineering[7]. Its core technical principle lies in the combination of prestress application and high-strength concrete performance. During prefabrication, pre-compressive stress is applied to steel reinforcements of pipe piles. Before bearing superstructure loads, compressive-stress equilibrium state is formed inside pile members. When pipe piles are installed into soft soils and subjected to superstructure loads, tensile stress induced by external loads first counteracts pre-compressive stress inside piles. Cracks will only occur when tensile stress exceeds the sum of pre-compressive stress and concrete tensile strength. This characteristic greatly improves crack-resistance performance and bearing capacity of pipe piles, making them adapt to high-load demands in soft-soil areas. Meanwhile, prestressed concrete pipe piles are manufactured by centrifugal forming and steam-curing processes. The concrete strength grade is generally no less than C80. Dense pile-body concrete provides favourable durability against corrosive agents in soft soils and extends the design service life of engineering structures.

Prior to construction of production piles for this project, three PHC-500(100) test piles are installed to provide basis for design. Two piles are used for verification single-pile vertical compressive static-load tests loaded up to design control load. The third pile is further loaded to failure state after reaching design control load as a destructive test pile, so as to

obtain complete load-settlement characteristics in the failure stage of pile foundations. The slow maintained-load test method is adopted. Load is applied step-by-step according to

specification requirements. Holding-load duration and pile-top-settlement observation frequency are strictly controlled. Recorded test results are summarized in Table 3.

Table 3. Measured Results of Single-Pile Vertical Compressive Static-Load Test

Pile No.	Pile diameter (mm)	Ultimate bearing capacity(kN)	Settlement at ultimate load(mm)	Maximum test load (kN)	Settlement at maximum test load(mm)
SZ1	500	2860	7.02	2860	7.02
SZ2	500	2860	6.39	2860	6.39
SZ3(destructive test pile)	500	2860	11.81	3120	41.21

3.3 Analysis of Engineering Deviation

Standard values of pile-shaft resistance and pile-tip resistance extracted from geotechnical -investigation reports are adopted as basic design parameters. Geological-profile data and pile-length data corresponding to destructive test pile SZ3 are substituted into Formula (1) for calculating single-pile ultimate bearing-capacity standard value, and the theoretical calculation result reaches 3147.6 kN. However, measured ultimate bearing capacity from field destructive static-load test is merely 2860 kN. Theoretical calculation value is 10.1 % higher than measured bearing capacity. Safety reserve obtained purely from theoretical calculation cannot satisfy engineering requirements. The core reason for such deviation is that conventional design only adopts representative standard soil-layer indexes and ignores extreme adverse working conditions where multi-layer soil parameters drop to low values simultaneously. After technical demonstration, engineering disposal scheme is determined: increase pile-tip penetration depth into medium coarse-sand bearing stratum from original 2.0 m to 2.5 m. After adjustment, pile-foundation bearing capacity meets design-control requirements. Cost estimation indicates that this design change caused by soil-parameter discreteness and design parameter-selection deviation increases total project investment by about 200 000 RMB and prolongs construction period by 12 d.

4. Differentiated Mechanism of Soil Discreteness

Based on 136 groups of laboratory geotechnical tests and eight complete static cone penetration-test profiles collected on-site, this paper decomposes degradation effects induced by parameter fluctuation of different soil layers on pile-shaft friction resistance and pile-tip

resistance, quantitatively distinguishes contribution weight of each stratum to bearing-capacity deviation, systematically interprets the intrinsic coupling-attenuation mechanism caused by simultaneous low-value states of multi-layer soils, and fully reveals stratigraphic origins for discrepancies between design values and field measured values.

4.1 Dominant Stratum for Pile-Bearing-Capacity Deviation

Stratum ③₁ silty-mucky clay is the soft stratum with highest discreteness over the site. It continuously distributes along most sections of pile shafts with thickness ranging from 4.3 m to 7.8 m and contributes more than 20 % to total pile-shaft resistance. Parameter fluctuation of this stratum constitutes the core inducement for over-estimated bearing capacity and excessive pile-top settlement. From micro-structural perspective, this soft soil has flocculent clay skeleton filled with free pore water and weak cementation. Disturbance caused by borehole sampling and static jacked-pile construction damages original flocculent fabric. Pore water cannot dissipate rapidly; effective stress drops within short time and soil strength suffers irreversible degradation[8-10].

According to static cone penetration-test data, the minimum sleeve-friction resistance of this stratum is only 6 kPa, which accounts for 60 % of average value and brings obvious shaft resistance reduction in local weak zones. It is difficult to distinguish respective contributions of single-stratum weakening and multi-layer simultaneous weakening only from results of one destructive test pile. To quantify coupling-attenuation effect, two sets of parameters (standard values and measured minimum values) derived from field geotechnical and static cone penetration tests are adopted. Pile length and pile-tip penetration depth keep consistent with test pile SZ3. Three calculation scenarios are set according to

Formula (1), and bearing capacity attenuation amplitudes are compared as listed in Table 4.

Table 4. Calculated Results of Single-Pile Ultimate Bearing Capacity

Calculation scenario	Parameter scheme	Single-pile ultimate bearing capacity (kN)	Attenuation amplitude relative to benchmark scenario
Benchmark scenario	All layers adopt standard values	3147.6	-
Single-stratum low-value scenario	Only stratum ③ ₁ adopts measured minimum value	2902.3	7.8%
Multi-layer coupling low-value scenario	Relevant layers adopt measured minimum values	2774.1	11.2%

Calculation results show that when only silty-mucky-clay parameters drop to measured minimum values, single-pile bearing capacity decreases by 7.8%. When multiple soft soil layers stay in low-parameter states simultaneously, bearing-capacity attenuation further rises to 11.2%, which reflects multi-layer-soil low-value coupling-attenuation effect. The reduction caused by low parameters of silty-mucky clay accounts for most proportion of total deviation induced by multi-layer low value conditions. The measured ultimate bearing capacity of destructive test pile SZ3 is 2860 kN, falling between calculation results of single-stratum low-value scenario and multilayer coupling low-value scenario, which reflects real-world engineering conditions where partial soil layers exhibit low mechanical indexes simultaneously. Settlement observation data of three test piles are compared. SZ2 is located where silty-mucky-clay layer is thin; its settlement is only 6.39 mm under load of 2860 kN. For destructive test pile SZ3 with thicker silty-mucky-clay deposit, settlement reaches 11.81 mm under the same load. The settlement difference expands to 41.21 mm under maximum test load. This comparison fully proves that discreteness of silty-mucky clay directly controls the magnitude of pile deformation and is the dominant stratum for engineering deviation.

4.2 Limitation of Pile-Tip Bearing Stratum in Eliminating Soil-Discreteness-Induced Deviation

Medium-coarse-sand bearing stratum ⑤ has well-sorted particles, stable sedimentary environment and no weak interlayers. Its mechanical-parameter fluctuation range is within 20%. Ultimate pile-tip resistance is mainly provided by this bearing stratum; nevertheless, its contribution to total single-pile ultimate bearing capacity is merely 17%. When synchronous shaft-resistance degradation

occurs in upper soil layers, additional tip resistance supplied by bearing stratum cannot compensate total loss of pile bearing capacity. Even with favourable bearing-stratum conditions, measured pile bearing capacity may still fail design expectations if low-value combination of upper silty clay and fine-sand -interbedded-silt layers is ignored in design phase. This phenomenon originates from superimposed resistance reduction caused by upper-soil-parameter discreteness, which leads to calculation deviation between theoretical values and field measurements due to multi-layer-soil low-value coupling-attenuation effect.

4.3 Groundwater Aggravating Soil-Parameter Discreteness

Perched water and deep confined-water infiltrate soft-soil strata and further enlarge parameter-fluctuation ranges. Seasonal water-level variation of perched water triggers repeated drying-wetting cycles for shallow fill and silty-clay soils, destroys soil internal fabric and degrades mechanical performance[8]. Long-term immersion by confined water with stable hydraulic head maintains high pore-water pressure inside silty-mucky clay, reduces effective stress and increases intra-stratum strength discrepancy. Groundwater-induced weakening effect enlarges gaps between standard values from geotechnical investigation and field low-value ranges and aggravates bearing-capacity-prediction deviation. Hydro-geological conditions should be comprehensively considered in soil-discreteness analysis[11-12].

5. Pile-Foundation Optimization Scheme Based on Stratified Soil-Discreteness Characteristics

Combined with complete geotechnical datasets, static cone penetration-test statistics and rectification experience from field test-pile

project, targeted optimization measures are proposed from perspectives of geotechnical-investigation layout and stratified soil-parameter selection. All measures are derived from soil-discreteness effect of this site to mitigate bearing capacity prediction deviation induced by design practice.

5.1 Optimization Rules for Investigation Layout and Undisturbed-Soil Sampling

(1) Optimize exploration-hole layout: reduce borehole spacing from 35 m to 20 m, so as to avoid missing local weak lenticular soil bodies and low-value soil zones;

(2) Optimize undisturbed-soil-sampling intervals: shorten sampling interval of stratum ③₁ silty-mucky clay from 1.2 m to 0.8 m to compensate discontinuity of soil samples obtained from borehole drilling;

(3) Optimize deliverables of geotechnical-investigation reports: not only provide standard representative values, but also list measured minimum, average and maximum values for each soil stratum with discreteness intervals clearly marked for designers' reference, so as to mitigate prediction deviation originating from geotechnical-investigation phase.

5.2 Auxiliary Construction-Phase Control Measures

Apart from geotechnical-investigation and design-phase optimization, construction-phase control measures can be adopted to mitigate adverse effects caused by soil-parameter discreteness:

(1) Static jacked-pile construction control: adopt slow-speed intermittent jacking technology. Prolong time interval between successive jacking operations to provide drainage channels for pore water in silty.

(2) mucky clay, mitigate irreversible strength degradation induced by construction disturbance and reduce actual shaft-resistance reduction magnitude;

(2) Long-term settlement monitoring: arrange settlement observation points on structures. Monitor deformation under empty-water and full-load working conditions. Pre-treatment measures such as grouting reinforcement can be adopted in advance if continuous settlement growth is detected.

6. Conclusion

This paper takes a PHC pipe-pile project built on an alluvial-lacustrine depression in Wuhan as research background. Relying on geotechnical laboratory tests, static cone penetration tests and destructive full-scale static-load-test data, multi-scenario parametric calculations are performed to analyse influences of alluvial lacustrine soft-soil discreteness on single-pile bearing capacity. The multi-layer-soil low-value coupling-attenuation effect and superimposed weakening effect induced by groundwater are revealed. Main conclusions are drawn as follows:

(1) Obvious stratification difference exists in soil-parameter discreteness within alluvial-lacustrine soft-soil site. Silty-mucky clay is the dominant stratum controlling bearing capacity and settlement of PHC pipe piles. Scenario-based parametric calculation indicates that single-pile ultimate bearing capacity decreases by 7.8 % when parameters of this soft stratum drop to measured minimum values. Multi-layer soils simultaneously adopting low-value indexes produce the low-value coupling-attenuation effect. Direct adoption of standard shaft-tip-resistance indexes of soil layers in this site yields theoretical bearing-capacity values 10.1 % higher than measured values from destructive static-load tests.

(2) Combined application of laboratory geotechnical tests, static cone penetration tests and multi-scenario calculation can quantitatively distinguish influences of soil-layer discreteness on bearing-capacity deviation. Groundwater infiltration amplifies soil-parameter fluctuation, which reveals internal mechanism for discrepancies between theoretical calculation values and field-measured values from the perspective of stratum-hydrogeology coupling.

(3) Complete sets of investigation-design-construction control strategies can be formulated according to soil-discreteness characteristics: densify exploration boreholes and undisturbed-soil sampling in investigation phase; adopt multi-index stratified-parameter-selection strategy in design phase; optimize intermittent jacking construction technology during pile installation and implement long-term settlement monitoring. These measures can narrow prediction deviation between calculated

bearing capacity and engineering reality and reduce risks of engineering change in investment and construction-schedule.

(4) The multi-layer-soil low-value coupling-attenuation effect analysed in this paper is derived merely from investigation and test-pile data of this single alluvial-lacustrine soft-soil project. Attenuation amplitudes vary under different regional stratigraphic combinations, stratum thicknesses and sedimentary-environment conditions. Further verification by more practical-engineering samples is still required for its universality.

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