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Research and Development of Laboratory Experiments on the Static Characteristics of Pile-Soil Contact Surfaces

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Abstract: ***This paper systematically investigates the mechanical properties of contact surfaces between soil and piles under static loading conditions across various scenarios through comprehensive laboratory experiments. The study offers an overview of current experimental equipment and testing protocols, succinctly describes the mechanical characteristics of pile-soil contact surfaces influenced by multiple factors, and summarizes existing constitutive models related to these interfaces. The objective of this research is to provide a more accurate and reliable laboratory methodology for analyzing the static mechanical properties of pile-soil contact surfaces, thereby fostering innovative advancements in the safety of pile foundations.***

Keywords: Pile-Soil Contact Surfaces, Laboratory experiments, Constitutive Model.

1. Introduction

In contemporary construction practices, the investigation of complex geological conditions has become increasingly comprehensive. In urban development, whether it pertains to civil engineering, road construction, bridge design, or slope engineering, assessing the bearing capacity of the interface between structures and soil is becoming progressively vital—particularly for concrete structures, which are among the most commonly utilized. Consequently, understanding both the bearing capacity and underlying principles governing structure-soil interactions is essential. This study emphasizes not only the inherent bearing capacities of both soil and structure but also highlights the critical importance of examining the bearing capacity at their contact surface. This is especially pertinent when considering lateral friction piles; thus, one must not overlook the mechanical characteristics associated with pile-soil interfaces. Furthermore, exploring these mechanical properties holds significant implications for research on negative friction piles [1].

In recent years, the continuous advancement of testing technology and equipment has led to the widespread application and development of laboratory experiments in studying the static characteristics of pile-soil contact surfaces. These experimental investigations not only provide crucial parameter support for pile foundation design but also yield experimental data essential for establishing and validating constitutive models. This paper aims to systematically explore the mechanical properties of contact surfaces between various soil types and pile materials under static loading conditions through comprehensive laboratory experiments. The research encompasses several key aspects: an overview of current experimental equipment and testing protocols; a brief introduction to the mechanical properties of pile-soil contact surfaces influenced by various factors; a summary of existing constitutive models pertaining to these interfaces, along with an introduction to their foundational theories. It is anticipated that this study will offer more accurate and reliable methodologies for analyzing the statics of pile-soil contact surfaces derived from laboratory experiments, thereby facilitating innovative advancements in ensuring the safety of pile foundations.

2. Experimental Equipment and Test Scheme

The static experiment serves as an effective approach for investigating the complex interactions at the pile-soil contact surface. This research holds significant implications for the theoretical understanding of both negative side friction resistance in piles and the mitigation of uneven settlement in pile foundations. Currently, various methods such as direct shear, single shear, and ring shear are employed in static experiments to analyze the pile-soil interface.

CLOUGH [2] conducted a study on the mechanical properties of sand and concrete structural planes through direct shear testing. DESAI CS [3] conducted direct shear tests that simulate both translational and torsional deformation modes under dynamic and static loading conditions using a self-designed cyclic multi-degree of freedom (CYMDOF) shear device. Lu Yanhao [4] effectively addressed the issues of size effect and edge stress concentration inherent in traditional direct shear tests by modifying the participating shear area of the structure. The experimental apparatus for pile-soil interface direct shear testing can be categorized into three types based on boundary conditions: constant pressure direct shear instrument, constant stiffness direct shear instrument, and constant volume direct shear instrument. Zhang Ga [5] developed a large-scale cyclic shear test device (TH-20t CSASSI), which enabled the comparative testing of three different boundary conditions through the control of an air bag and a spring mechanism. Upon comparison, it was determined that both the constant stiffness and constant pressure direct shear instruments are more representative of actual conditions. Wang Yonghong et al. [6] employed an idealized spring system to implement an experimental scheme that maintains constant stiffness for examining the cutting characteristics of large soil loading interfaces.

For large-scale laboratory tests, it is recommended to utilize a single shear test apparatus to investigate the mechanical properties of the soil-concrete structural interface. This approach ensures a uniform stress distribution across the shear plane. UESUGI M [7] modified the previous single shear experimental device to record the friction process at the interface between sand and steel. This was achieved by incorporating a glass window into the sand loading frame, allowing for direct observation of the interaction. Zhou Xiaowen [8] and Zhang Zhijun [9] conducted experimental investigations to assess the impact of mud skin on the surfaces of concrete, cement sand, and asphalt. They also examined how water content influences the mechanical properties at the interface between sand and gravel soil. This research utilized a large-scale laminated ring single shear instrument developed by the Yangtze River Scientific Research Institute. For static testing of soil and structural planes with significant displacement, it is recommended to employ a ring shear test device. Yoshimi U [10] has investigated the static properties of the interface between sand and metal utilizing a cyclic torsional shear device. Cheng Zehai [11] compared the differences between the direct shear method and the torsional shear method in examining the mechanical properties of pile-soil interfaces. He proposed that the torsional shear method can effectively address issues related to vertical stress eccentricity and uneven distribution of shear stress inherent in direct shear devices. Furthermore, he presented an experimental apparatus and testing protocol tailored for the application of the torsional shear method. Zhou Kai [12] employed the principle of a direct shear device for soil testing to apply a normal force using a jack, while controlling the magnitude with a stress ring. This approach facilitated a straightforward direct shear test of the pile-soil interface. Cheng Hao [13] employed a large multifunctional interface direct shear tester, TAW-800, in the experiment. This apparatus consists of a shear box, horizontal and vertical loading systems, as well as a computer control and data acquisition system. It is capable of conducting shear tests under complex stress paths, including unidirectional shear and cyclic shear. In the current research, an enhanced version of the geoshear testing instrument—controlled by either constant displacement or constant load—is predominantly utilized.

3. Influencing Factors

The shear force at the pile-soil interface is a critical factor in the design and analysis of pile foundations, as it directly influences both the bearing capacity and stability of these structures. In indoor static experiments examining the pile-soil contact surface, investigations into interfacial shear force typically encompass various aspects. Numerous factors impact the shear force at the pile-soil contact surface, which can generally be categorized into several key areas:

3.1 Types of Soil: Various types of soil, including sand, clay, and silt, exert different influences on the shear force at the pile-soil interface. Generally speaking, sand exhibits a higher angle of friction, whereas clay demonstrates greater cohesive strength. For sand, Wang Zhan [14] conducted a torsional shear experiment to investigate the interfacial shear characteristics between steel pipe piles and various types of sand. The findings revealed that after the interfacial shear force reaches stability, the interfacial shear stress exhibits slight fluctuations as the shear displacement increases. Furthermore, it was observed that larger particle sizes correspond to more pronounced fluctuations. However, the type of soil material has minimal impact on the ultimate shear force. For silt: Sang Songkui [15] conducted a comprehensive full-scale test on pile foundation engineering to analyze the variations in pore water pressure at the pile-soil interface. The findings revealed that both pore water pressure and excess pore water pressure are closely linked to the properties of soil layers. Notably, the increase in pore water pressure is more gradual within silt layers compared to a more rapid increase observed in silty clay layers. Furthermore, (ultra) pore water pressure emerges as a critical factor influencing shear force at the pile-soil interface; For clay: Kong Lingwei [16] conducted a simulation test on the soft clay that had been reconsolidated around the pile. The findings indicated that, following significant deformation, the peak strength and internal friction angle of the pile-soil interface decreased after reconsolidation of the surrounding soft clay. Additionally, it was observed that the shear displacement at which peak strength was attained was reduced. Conversely, both residual strength and its corresponding internal friction angle exhibited a slight increase, demonstrating characteristics of strength recovery. Regarding mixed soil properties in complex soil conditions, Kundsen [17] conducted an analysis of the characteristics of single piles in heterogeneous soil utilizing ABAQUS software. The study revealed that the soil resistance exhibited significant variations at the interface between silt and silt. For other soil types with unique properties, For instance, Zhu Zhuliang [18] observed that, in comparison to other soil types, the stress-strain curve of the expanded soil-concrete interface under varying water content conditions does not exhibit strain softening behavior. Instead, it predominantly aligns with the strain hardening model. Furthermore, its peak stress-strain value lags behind that of Xi'an. Qi Tian [19] employed a large indoor dynamic direct shear apparatus to perform various direct shear experiments on the interface between self-fabricated sulphated soil and concrete. The findings indicated that an increase in soil salt content enhances interfacial shear performance; however, excessively high salt concentrations can inhibit further strength improvements and lead to a decline after reaching a peak value. In general, the type of soil significantly influences the pile-soil interface shear force. This influence is primarily manifested in factors such as internal friction angle, cohesion, drainage capacity, compactness, and water content of the soil. Sandy soils are capable of sustaining relatively high shear forces over short durations. In contrast, the consolidation effects associated with clay and poor drainage characteristics result in a rapid decrease in shear force within brief timeframes. Meanwhile, changes in shear force for silt occur more gradually compared to both sandy and clayey soils.

3.2 Other Influencing Factors. In addition to the impact of soil quality on the shear force at the pile-soil interface, several other critical factors also play a significant role in determining the mechanical performance of this interface. These include soil moisture content, pile surface roughness, and the normal stress exerted by the surrounding soil on the pile surface. Furthermore, additional influences on interface shear force arise from factors such as shear rate, surface degradation of concrete due to freeze-thaw cycles, time-dependent soil displacement resulting from consolidation effects, and variations in stress distribution between piles and soil associated with different piling methods.

As for the water content, Guo Jukun [20] conducted an experimental study on the interface shear behavior between piles and marine clay. Utilizing an enhanced direct shear test apparatus, shear tests were performed on the interfaces of marine clay with steel and concrete at moisture contents of 20%, 40%, and 60%. The results indicate that under identical normal stress conditions, a higher moisture content in marine clay correlates with reduced peak shear stress and peak shear displacement at the interface. Chen Ronggang [21] conducted a study utilizing various soil types under three distinct water content conditions. The findings indicated that both the initial shear stiffness coefficient and the critical settlement required to achieve final lateral friction resistance are influenced by the type of soil and its water content. Notably, changes in water content had a significant impact on the final friction resistance of silt and fine sand, while exerting relatively minor effects on the final friction resistance of silty clay. The maximum final frictional resistance was observed at optimal water content conditions. Wang Yonghong [22] and Li Huaixin [23] conducted direct shear experiments on soil samples near the optimal moisture content. The results indicated that cohesion is influenced by the critical water content. When the water content is below this critical threshold, cohesion increases as water content rises. Conversely, when the water content surpasses the critical value, cohesion decreases with increasing moisture levels. In general, when the water content remains below the critical level, the cohesiveness of the interface between cohesive soil and concrete tends to improve with higher moisture levels. However, once this critical threshold is exceeded, both frictional force and internal cohesiveness within the soil diminish, leading to an overall decline in shear strength. This phenomenon occurs because increased moisture affects particle interactions within the soil matrix, thereby impacting its overall shear strength.

For the assessment of surface roughness, a widely used method for evaluating concrete surface texture is the sand filling depth technique [24], fractal dimension method [25][26], digital image processing technique [27] and grayscale image processing approach [28]. Wang You [29] conducted a comparative analysis of the exponential fitting model relating the mesh number of sandpaper to the interface roughness index. The findings indicate that the interface shear strength increases as a power function of roughness; however, the impact of roughness on shear strength diminishes with increasing normal stress. This suggests the existence of a critical value for roughness. Luo Yaowu [30] proposed a model experiment to investigate the influence of interface characteristics between piles and sand on the load-bearing behavior of pulled-out piles in sandy environments. The results indicate that for smooth piles, the load-bearing capacity stabilizes once the applied load reaches its ultimate bearing capacity. In contrast, rough piles exhibit a post-peak decline phenomenon along with residual bearing capacity, despite demonstrating higher overall bearing capacities. In conclusion, an increase in surface roughness enhances both the degree of interlocking and the anti-sliding friction strength at the contact interface, thereby improving the shear strength of the pile.

Secondly, Yu Hai [31] conducted an investigation into the relationship among normal stress, shear stress, and shear displacement at the pile-soil interface through large-scale direct shear experiments. The findings indicate that the relationship among normal stress, shear stress, and shear displacement can be accurately represented by a hyperbolic function. In this model, parameter c exhibits a linear correlation with normal stress. Wang Yonghong [32] and Kong Lingwei [15] conducted direct shear and ring shear experiments on the pile-clay interface. The experimental results indicate that both the shear strength and internal friction angle of the soil exhibit a monotonically increasing trend with rising shear strain rate, whereas cohesion demonstrates an inverse relationship. As the shear rate increases, there is a significant enhancement in both peak shear strength and peak displacement. The experimental findings of Xu Xiaofeng [33] indicate that the softening of the shear stress-displacement curve becomes increasingly pronounced with an elevation in shear rate. Wang Boxin [34] investigated the impact of freeze-thaw cycles on the shear properties of the silty clay-concrete interface. The study revealed that freeze-thaw conditions alter the contact mechanisms between soil particles, leading to a gradual deterioration in the shear properties of this interface. As the number of freeze-thaw cycles increases, there is a corresponding decline in shear strength, cohesion, and internal friction angle.

4. Constitutive Model

The constitutive model of the pile-soil interface shear effectively describes the interaction between the pile foundation structure and the surrounding soil, particularly in terms of shear behavior. This modeling is crucial for accurately predicting both the bearing capacity and settlement characteristics of pile foundations. Various constitutive models can capture the unique properties associated with different soil types as well as the operational states of pile foundations. Based on their inherent contact behavior, constitutive models for pile-soil contact surfaces can be categorized into two main types: contact surface constitutive models and contact element constitutive models.

4.1 Constitutive Model of the Contact Element

Goodman [35] examines the discontinuity of contact elements in relation to slippage and swelling, and develops a thick-less element featuring four nodes. Desai [36] proposed a thin-shell element that utilizes shear stiffness and normal stiffness determined through shear testing. This approach effectively addresses the issue of arbitrariness associated with the values of normal stiffness used by previous researchers. Based on the work of Goodman and Desai, Shao Wei [37] proposed a hybrid iterative model that integrates excess stress conversion and embedding adjustment. This model aims to enhance the accuracy of contact thin shell elements by addressing the nonlinear characteristics of both normal and tangential forces at the contact surface. On this basis, Du Chengbin [38] employed the strain hardening hyperbolic model to characterize the nonlinear properties of both the normal and tangential forces at the contact surface. He subsequently proposed a three-dimensional nonlinear contact element. Yin Zongze [39] demonstrated through direct shear tests that the relationship between the relative displacement of the shear box and the average shear stress is not unique; rather, it varies with size. This indicates that shear failure can be characterized as rigid-plastic behavior. Building on this finding, a type of contact element with thickness has been proposed, along with an approximate range for its thickness. Uesugi [40] initially introduced the concept of shear bands while investigating the mechanical properties of the contact interface between sand and rough steel. It is important to note that this shear band phenomenon does not apply to smooth surfaces. Kraft [41] and Randolph [42] proposed a theoretical model for the settlement of pile foundations, which incorporates shear zone theory to account for pile-soil interaction. Hu Liming [43] employed digital photography to document the displacement of sand particles at the interface and conducted an analysis of the deformation mechanisms occurring at the soil-structure interface during shear failure. The Useugi perspective is reaffirmed, with a quantification of the critical value for smooth surfaces provided, along with approximate data regarding shear zone thickness. WANG [44] demonstrated that the thickness of the shear zone is correlated with both the roughness and the volume of grouting, as evidenced by direct shear tests conducted on grouting clay and concrete.

In general, the constitutive model of the pile-soil interface contact element evolves progressively from a negligible thickness to a measurable thickness. The shear zone theory, which accounts for the nonlinear characteristics of the dislocation-shear curve, has garnered significant attention in contemporary research. Examining its distribution and influencing factors remains a critical topic in modern studies.

4.2 Constitutive Model of Contact Surface

The constitutive model for the shear force at the pile-soil contact surface is employed to characterize the interaction between the pile foundation structure and the surrounding soil, particularly in terms of shear force behavior. Various constitutive models can effectively represent the characteristics of different soil types as well as the operational state of the pile foundation. Below are some commonly utilized constitutive models for shear force at the pile-soil interface: hyperbolic model, rigid-plastic model, elastic-plastic model, and damage model.

Literature [2] initially established the hyperbolic model based on the relationship between shear strength and water content. However, this model proved to be overly simplistic for more complex scenarios. Ye Jianzhong investigated the friction resistance mechanism of cast-in piles and proposed a range of calculation parameters pertinent to the hyperbolic friction resistance model. The findings indicate that employing a hyperbolic function is a reasonable approach to elucidate the correlation between friction resistance and relative displacement, demonstrating a clear dependence on time. Cao Weiping [45] refined the hyperbolic model to account for the increase in initial shear stiffness of the interface, which arises from the consolidation of the surrounding soil. This modification aims to better align with the development of neutral points in negative friction piles. Wang Weidong [46] further refined the hyperbolic model based on experimental results from super-long cast-in-place pile-soil interactions. He categorized the model into three distinct modes: softening type, hardening type, and mixed type, simulating each in stages. The developed model effectively and accurately calculates the load-displacement behavior of super-long bored piles. Boulon [47] was the first to propose the elastic-plastic model theory; however, its complexity posed challenges in research, and no appropriate conditions for application were established. Wang Chenghua [48] employed the Mohr-Coulomb elastoplastic constitutive model to simulate soil behavior and utilized contact surface units to represent pile-soil interactions. A numerical analysis of the vertical load response of a pile group foundation, taking into account the effects of pit excavation, is presented through the establishment of a three-dimensional finite element model. Zhang Zhiyuan [49] conducted extensive direct shear tests to investigate the shear strength and expansion characteristics of the interface. The findings indicate that these characteristics align with the elastoplastic hardening model, influenced by varying water content and normal stress levels. Ye Shuaihua [50] discovered that the pile-soil bond slip model aligns with the ideal elastic-plastic model. Specifically, the relative displacement at the pile-soil interface and the shear displacement of soil within the shear zone adjacent to this interface adhere to the principle of superposition. By developing an elastic-plastic theoretical framework for pile-soil interaction and integrating it with empirical data, a more accurate prediction of both settlement and bearing capacity for individual piles can be achieved. DESAI [51] was the first to incorporate a damage model into the characterization of the constitutive relationship at the contact surface. Building upon damage theory, Li Sai [52][53] enhanced the constitutive model of the thicknessless contact surface by incorporating the depth effect of the initial shear strength at the pile-soil interface. This model preserves uniformity in both shear stress and shear strain across the thickness direction of the contact surface, effectively aligning with the mechanical behavior observed under low normal forces. However, further research is required to address its performance under high normal forces. Literature [39] suggests that the dislocation of the contact surface progresses gradually from the interior to the exterior, and shear failure develops incrementally throughout most of the shearing process. Consequently, the steel-plastic model was eliminated based on this understanding. Zhou Yong [54] proposed a computational model that employs rigid-plastic theory to simulate the soil characteristics surrounding the pile. In this model, the plastic region is represented by a series of spring elements. While it has been demonstrated that the model with the highest number of springs is feasible, it has not succeeded in yielding an exact solution.

Generally speaking, the elastoplastic model, damage model, and hyperbolic model have been utilized under their respective suitable conditions. While the steel-plastic model offers insights into shear band theory, it has not gained widespread acceptance. Future research should aim to achieve greater uniformity in this field.

5. Expectations and Prospects

The pile-soil interaction problem is a fundamental issue in geostructural engineering. Understanding the mechanical properties of the pile-soil contact interface is crucial for the advancement of pile foundations and, more broadly, soil-structure interactions. Based on prior research and analysis, the author posits that future trends and focal points in this area of study are as follows:

(1) In contemporary times, while there exists a plethora of laboratory experimental instruments, the majority are primarily based on direct shear tests for soil analysis. However, their adaptability to complex conditions or large-scale testing remains limited. Looking ahead, as experimental equipment and technology continue to advance, it is anticipated that more high-precision and highly adaptable experimental devices will emerge. These innovations will enable more accurate measurements of the mechanical properties at the pile-soil contact interface and provide more reliable data support.

(2) Future research is likely to advance in a multi-scale approach, encompassing experimental studies at macro, micro, and nano scales. Through these multi-scale experiments, the mechanical behavior of the pile-soil contact surface can be comprehensively elucidated, spanning from microstructural characteristics to macroscopic mechanical properties. This will provide a more systematic theoretical foundation for the design of pile foundations.

(3) Currently, a comprehensive consensus on the theoretical foundation has yet to be established. Future research should focus more on integrating numerical simulations with experimental investigations. It is essential to develop a more precise and reliable constitutive model for the pile-soil contact interface through numerical simulation techniques (such as finite element analysis and discrete element analysis) alongside reciprocal validation of experimental data. This approach aims to enhance both the reliability and applicability of simulation outcomes.

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