Axial Performance of Steel Piles in Sand and their Implications for Polymer-Based Coatings, Composite Strengthening, and Soil–Polymer Interaction Systems

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Abstract: Polymer-based coatings, composite wraps, and functional polymer interfaces are increasingly used to enhance the durability and axial performance of steel piles in infrastructure applications. The establishment of baseline behavior of uncoated piles is a prerequisite for the design of integrated polymer systems. This paper presents an experimental comparison of the axial performance of H-section steel and closed-ended pipe piles embedded in poorly graded sand (SP) at 58% relative density. Eighteen static load tests were carried out on single piles and 2-pile and 4-pile groups using L/D ratios of 10 and 15. H-piles consistently demonstrated higher ultimate capacities because of soil plug formation, better interface shear mobilization, and densification during driving. Capacity gains with increasing L/D were as high as 109%, and up to 365% in H-pile groups. The test results establish a benchmark dataset for developing polymer-coated, polymer-modified, and FRP-strengthened pile systems and contribute to advances in polymer applications in geotechnical and infrastructure engineering.

Keywords: Polymer-coated pile, fiber reinforced polymers, soil-pile interaction, H-section steel piles, closed pipe stacks, axial load capacity, Earth plug formation.

1. INTRODUCTION

Steel piles form the core of deep foundation systems due to their high structural efficiency in transferring loads to competent soil levels and versatility in bridges, buildings, transport corridors, energy facilities and coastal structures [1-3]. Axial behavior is developed as a complex interaction between soil type and conditions, installation method, pile geometry and mode of load transfer. In recent decades, the incorporation of polymer-based materials into civil engineering applications has significantly expanded the functional capacity of steel piles [4–6]. Consequently, polymer coatings, FRP wraps, polymer modified interfaces and advanced polymer composite systems are increasingly used to improve durability, reduce corrosion, alter load transfer properties and provide increased service life in hostile environments [7–9]. Styrene-butadiene rubber (SBR) latex is often used in polymer-modified concrete to increase bond, reduce permeability, and improve durability. In steel pile applications, SBR-modified concrete can improve the concrete-steel interface, which is critical for effective axial load transfer and settlement control, especially in sandy soils where pile performance is controlled by interface behavior. The elastic properties of the polymer also help to reduce stress concentrations around the pile, supporting improved axial performance without altering traditional load transfer mechanisms. As these technologies continue to mature, an accurate understanding of the fundamental mechanical behavior of uncoated steel piles becomes increasingly important to guide the design and optimization of polymer-reinforced pile systems.

The relevance of polymer science to foundation systems goes far beyond simple corrosion protection. Functional polymer coatings can significantly change the surface roughness, adhesion properties and microtexture at the pile-soil interface, which directly affects the shaft friction and bond strength in granular soils [10–12]. Composite systems such as FRP wraps can enhance confinement, increase stiffness, and alter the distribution of stress transfer along the shaft or near the pile toe. Current research is also being conducted into polymer-modified surface treatments—epoxy-based coatings or polyurethane interfaces—that appear to enhance interaction with sands and provide some resistance to abrasive soil minerals [13–15]. These emerging technologies provide a further strong motivation for comprehensive mechanical benchmarks that describe the behaviour of traditional uncoated piles, so that the influence of polymer modifications can be quantified. In the absence of such baseline data, the development of advanced polymer-enhanced piles and composite strengthening systems is without the necessary reference against which performance might usefully be compared [16–18].

Many researchers, over the past several decades, have studied the mechanics of vertically loaded piles. The seminal studies by Randolph, Tomlinson, Uge, and Islam developed the understanding of load transfer mechanisms concerning shaft friction mobilization, end-bearing resistance, soil densification around driven piles, and installation effects on stress redistribution [19–23]. They emphasized that pile behavior is sensitive to changes in soil density, pile size, relative displacement and boundary conditions. In particular, displacement piles such as closed tube piles often benefit from densification and increased horizontal stresses developed during driving, while

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non-displacement piles such as H-piles may be more dependent on shaft interactions and internal soil behavior. There has also been significant development in research into soil plug formation. It has been investigated that plugging in tubular or H-shaped sections can significantly increase the stiffness and change the load transfer characteristics of the elements, transforming them from open to partially plugged systems [24–25]. Despite the above insights, results vary due to different soil types, pile geometry, test conditions and installation method.

While the above literature represents a strong theoretical and experimental background, it also shows several limitations. A significant number of studies on one type of pile – either H-section pile or tube pile – have been carried out without direct experimental comparison under similar conditions. Many studies have been conducted with different relative densities, embedment depths, or test setups, making reliable conclusions about how geometry alone affects axial behavior difficult to achieve [26–28]. Only a few investigations have evaluated pile groups, although group behaviour is essential to understand soil arching, lateral confinement, and the interaction of stresses among adjacent shafts [29–30]. Variations in the soil plug formation, particularly in H-piles, have also been documented quite inconsistently, with certain researchers observing clear plug development and others noting minimal internal soil retention depending on the soil gradation and driving method. Furthermore, while polymer-modified piles are gaining increased usage, there is still a fundamental lack of comparative data describing how uncoated steel piles perform under controlled conditions that can serve as a reference against which the benefits of polymer coatings, polymer–soil interfaces, and FRP strengthening systems can be assessed.

This gap in traditional geotechnical studies and emerging polymer-integrated technologies is most relevant to journals dealing with material science and polymer research. Polymer coatings and composite materials are currently designed to optimize not only durability but also mechanical performance, such as modifying frictional behavior, improving interface shear strength, and optimizing load transfer in sandy conditions. Further understanding of uncoated pile behavior in uniform sand conditions-as individual members and within groups-provides key insights into how polymer modification affects shaft behavior, confining pressures, soil densification, and mobilization of end-bearing. For instance, if H-piles naturally generate a soil plug that enhances stiffness and load capacity due to internal side friction, polymer-based systems may be newly designed to control or promote the retention of the soil within cross-sections. In this same manner, the effects of surface roughness observed in steel piles can be used to develop specially engineered polymer coatings for increasing the micromechanical interlocking. Therefore, the emergent interface between geotechnical engineering and polymer science necessitates the establishment of a clear-cut mechanical reference prior to the incorporation of surface or structural modifications.

Motivated by these considerations, this study focuses on a well-defined research gap: a lack of controlled experimental data that is comparative for H-section steel and closed-ended pipe piles subjected to identical soil conditions with identical relative densities and under identical L/D ratios; few studies have considered both single piles and pile groups in the same study with the objective of formulating axial behaviour as a function of geometry, plugging, and group interaction. Even fewer have framed these findings in a manner that supports the development of polymer-coated or composite-strengthened pile systems. The lack of unified experimental datasets poses challenges for materials scientists and polymer engineers seeking to quantify the improvements achieved through polymer modifications.

In this work, eighteen controlled static load tests on H-section piles and closed-ended pipe piles embedded in poorly graded sands (SP) at a fixed relative density of 58% were conducted to address this gap. The study considers the performance of single piles and 2-pile and 4-pile groups, each with nominal L/D ratios of 10 and 15, to isolate the impact of geometry, soil confinement, and plugging on ultimate capacity. This approach removes the inconsistencies prevalent in previous studies; provides, for the first time, a direct mechanical comparison between the pile types; and provides insight into how plugging, mobilization of shaft friction, and driving-induced densification interact to provide axial capacity, particularly in granular soils. These insights will be crucial for the design of next-generation polymer-enhanced pile systems, polymer–soil interface technologies, and composite confinement solutions.

This paper contributes new knowledge in the following ways:

1. Providing a uniform experimental comparison between H-piles and closed-ended pipe piles under identical test conditions.
2. Explain the role that soil plug formation and geometry-driven differences in load transfer play.
3. Quantifying group effects related to confinement and soil arching.

4. Establishing the essential baseline behaviour required to evaluate polymer-coated and composite-strengthened piles.

This work thus forms a bridge between geotechnical engineering and polymer materials research by providing the data and analysis that are useful in advancing polymer-based solutions in construction, transportation, energy, and environmental engineering. Importantly, the mechanism of soil plug formation in pipe piles and H-section piles is quite different: while the pipe pile starts to develop a full plug, the H-pile develops partial plugging in the flange–web region as shown in Figure **1** for the case study at hand. Fattah *et al*., 2016 .

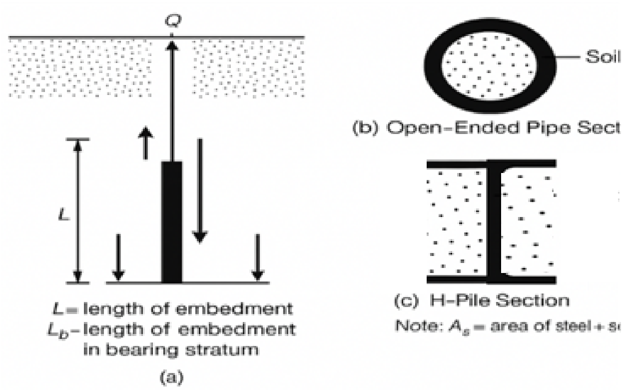

Figure 1: Schematic of soil plug formation in closed-ended pipe piles and H-section piles (adapted from Fattah *et al*., 2016).

2. MATERIALS AND METHODS

The experimental program presented in this paper was undertaken to provide a controlled and systematic comparative study of the axial performance of closed-ended pipe piles and H-section steel piles embedded in poorly graded sand (SP); this program was conducted using model-scale tests under uniform soil density and consistent installation and standardized loading conditions. Sand samples were obtained from the north part of Al-Najaf city and subjected to a set of tests for physical characterization at the Civil Engineering Department, University of Kufa. The grain size distribution was determined according to ASTM D422, confirming that the soil was composed of about 96.5–97.4% sand with very small fines, and the coefficients of uniformity and curvature are given by Cu = 3.89 and Cc = 0.49; it thus falls within the category of poorly graded sand (SP) according to the USCS system. Other soil properties measured according to the corresponding ASTM standards include the specific gravity, obtained based on ASTM D854, the recorded value of which was 2.60–2.61, while the maximum and minimum dry unit weights, measured based on ASTM D4253 and ASTM D4254, respectively, are 18.5 kN/m³ and 15.5 kN/m³. The average intermediate dry unit weight of 17.09 kN/m³ corresponding to a relative density of 58% was selected for the testing program, which was attained through controlled sand placement in layers using a calibrated raining technique that allowed for uniform deposition. The target density was verified through sand cone tests (ASTM D1556) applied at several locations after each layer was placed, and the moisture content was controlled to maintain the same conditions during all experiments. The two types of pile models prepared for testing included closed pipe piles and H-section steel piles. Pipe piles consist of circular steel pipes with bottom plates welded as closed ends to act as displacement piles. H-piles were produced by welding steel plates with a thickness of 4 mm to form symmetrical flanges and a central web, thus ensuring dimensional stability and corresponding cross-sectional area between the two pile types. Both piles were produced in two lengths to suit target L/D values of 10 and 15, with the width of the H-pile flange and web chosen to match the corresponding diameter of the pipe pile. In total, eighteen tests were carried out:

Table 1: Physical Properties of Poorly Graded sand (SP) that was used in the Experimental Program Along with Grain Size Distribution Parameters, Soil Classification Data, and Index Properties Determined in Accordance with ASTM Standards

Property	value	Specification
D_{60} (mm)	0.7	ASTM D422-2001
D_{30} (mm)	0.25	
D_{10} (mm)	0.18	
Gravel %	0%	
Sand %	97.4%	
Silt and Clay%	2.6%	
Specific gravity (Gs)	2.61	ASTM D854
Maximum dry unit weight (kN/m^3)	18.5	ASTM D4253
Minimum dry unit weight (kN/m^3)	15.5	ASTM D4254
Field density (kN/m^3)	17.09	ASTM D1556

single pile test, two pile group tests and four pile group tests for each pile type and L/D ratio. The tests were carried out in a rigid steel container of size 1200 × 1200 × 1200 mm, which was constructed from 4 mm thick steel plates to reduce lateral deformation and boundary effects; This size ensured that the minimum recommended lateral clearance of 10 to 12 pile diameters was maintained to prevent interference with tension zones around the pile.

The physical and classification properties of the sand used for all tests are provided in Table **1**, indicating that the soil is mostly sandy (97.4%) and contains very low fines content, which also meets the ASTM requirements for the grain size distribution, specific gravity, and measurements of the density of the tested soil. A guided pile installation system was adopted to ensure vertical driving and consistent alignment; it consisted of wooden panels with precisely machined holes to hold the piles in position, resting on vertically oriented tubular steel columns that sustained the alignment of the driving apparatus. The driving apparatus consisted of an aluminum rod fitted with a steel helmet designed with recesses matching the pile cross-sections to allow seating in a firm manner that reduces the deviation while driving. A steel cylinder drop weight was used to provide consistent hammer impact energy, and a mechanical jack was integrated into the setup to apply controlled downward pressure in the final stages of installation to ensure accuracy in embedment to the prescribed depth with minimum disturbance of the surrounding soil. Two types of piles were used in this study, namely closed-ended pipe piles and H-section steel piles, which were prepared in identical cross-sectional areas (presented in Figure **2**), so that any potential differences in performance would be due solely to geometry rather than material or size effects.

A steel loading frame was specially fabricated with the capacity to hold a hydraulic compression jack of 10-ton capacity. The frame also served as the reaction system in axial loading. Axial loadings were applied by a hand-operated hydraulic jack, while the load transmitted to the soil specimen was measured using a calibrated S-type load cell (model SM 600E) fabricated from stainless steel with a capacity of 5 tons. Load readings were displayed on a digital weighing indicator with a sensitivity of 50 g. Settlements at the pile head were measured from two digital dial gauges located

Figure 2: Model piles used in the experimental program, including closed-ended pipe piles and fabricated H-section piles designed with equivalent cross-sectional areas.

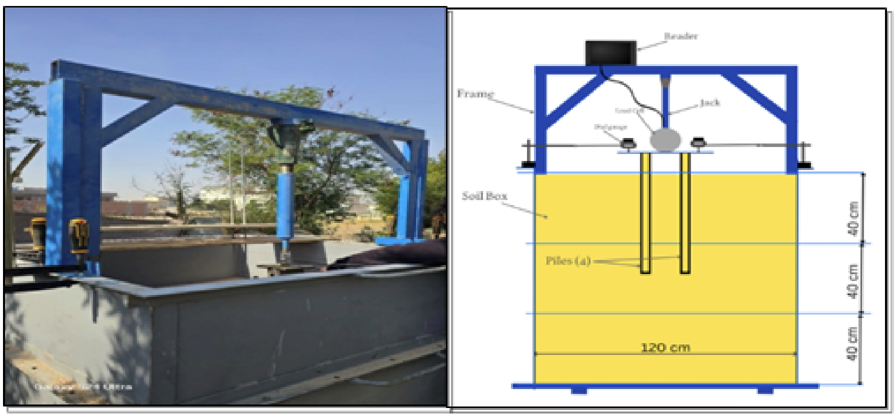

Figure 3: Steel loading frame and axial loading system used for static load testing, consisting of a rigid reaction frame, hydraulic compression jack, calibrated S-type load cell, and dual dial-gauge settlement measurement arrangement.

Figure 4: Pile group system installation showing the guided alignment frame, wooden positioning panels, and steel support columns used to ensure uniform spacing and verticality during driving of 2-pile and 4-pile group configurations.

opposite each other. The dial gauges have a reading stroke of 5 cm and an accuracy of 0.001 mm, thus allowing accurate measurement of vertical displacements with increasing loads. The following calibration procedures were undertaken before each series of tests: three-point static loading with known weights to calibrate the load cell; checks on the pressure-load consistency of the hydraulic jack; and verification of dial gauges against gauge blocks. Preparation of the sand bed prior to each test included pouring sand in layers into the tank and compacting it by a calibrated frame method until the required relative density was achieved. Verification of achieved density ensured evenness of the soil for pile installations. Verticality was checked using spirit level and laser leveling tools during piling, and any deviation of more than 2 mm in pile length was corrected. As shown in Figure **3**, static axial load tests were performed using a steel load frame and hydraulic jack arrangement, which ensured stable application, accurate measurement of load and monitoring of vertical settlement throughout the test.

The spacing and driving procedure for the 2-pile and 4-pile group tests were standardized by use of the guiding alignment frame and positioning system shown in Figure **4** to ensure consistent spacing, verticality, and uniform driving energy across all group configurations. Static load testing was performed following a slow maintenance loading (SML) procedure in which load was applied in increments of approximately 5–10% of the predicted ultimate capacity, and settlement readings were recorded after the deformation stabilized at each increment. Testing was continued until the load-settlement curve showed distinct non-linear behavior or the settlement exceeded approximately 10–15% of the pile width. In the pile groups, two- and four-pile configurations were installed with equal center-to-center spacing determined based on model scale considerations; All piles in a group

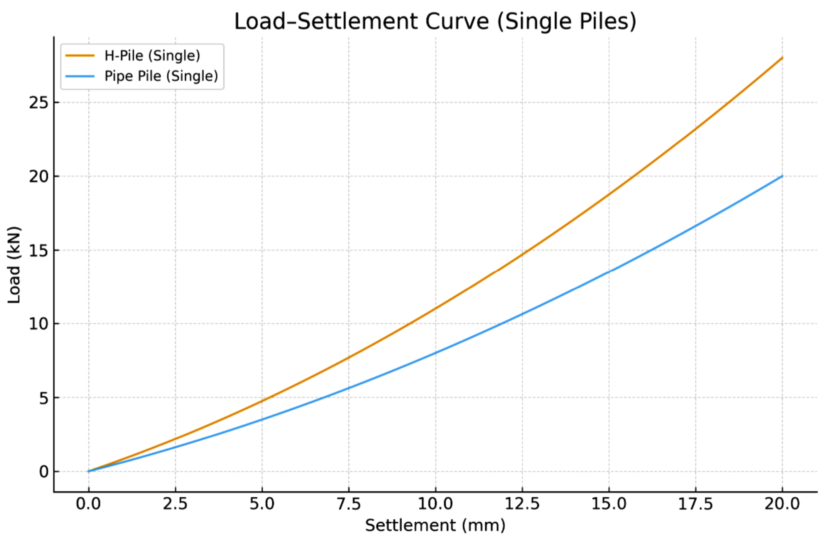

Figure 5: Load–settlement behaviour of single H-piles and closed-ended pipe piles embedded in medium-dense poorly graded sand.

were driven down before loading to maintain the consistency of the compaction effect. Load–settlement curves were generated for each test, and ultimate capacities were interpreted using generally accepted criteria such as tangent intersection, load–settlement curve behavior, and settlement equal to 10% of the pile diameter. Group efficiency factors were also calculated by comparing the measured capacity of group systems under identical conditions with the sum of individual stack capacities. Through the experimental program, attention was paid to ensuring that soil conditions, driving energy, alignment, loading procedures, and instrumentation remained uniform across all tests to facilitate a reliable comparison between the performance of H-piles and closed-ended pipe piles and support the interpretation of results based on soil–pile interaction mechanisms such as plugging, densification, shaft friction mobilization, and group effects.

3. RESULTS AND DISCUSSION

The experimental program clearly elucidates the axial load-settlement behavior, the variation of ultimate bearing capacity, and the group interaction of closed-ended pipe piles and driven H-section steel piles in medium-dense, poorly graded sand. Such differences are strongly influenced by pile geometry and embedment ratio, as well as by how the piles are grouped together. Load-settlement curves for single piles begin with a linear elastic response, then transition to nonlinear as shaft friction mobilizes and the end-bearing resistance increases with settlement. At L/D = 10, the H-piles start with higher initial stiffness and reach larger loads for a given change in curvature, which indicates more efficient mobilization of shaft friction compared to the pipe piles. The H-piles attain a considerably higher ultimate capacity in this setup due to an adequately developed in-situ soil plug within an open web, steeper stress concentration around the flange edges, and overall densification caused by driving.

While closed-ended pipe piles act like true displacement piles, they mobilize shaft friction at a significantly more gradual rate, which might be due to their smoother outside surfaces interacting less with the surrounding sand. They do tend to have a stronger end-bearing mobilization at greater settlements owing to effectively enlarged base area. When the embedment ratio increases from L/D 10 to 15, both pile types achieve notable gains in ultimate capacity, but pipes benefit more because extra embedment increases overburden pressure on the shaft and widens the active friction zone.

For the H-piles, lengthening the pile shows a clear capacity increase; however, the gains diminish with depth, reflecting the frictional saturation observed in the displacement piles where the deeper soils cease to provide proportional contributions beyond certain thresholds of effective stress. In the single-pile load–settlement plots presented in Figure **5**, the H-piles demonstrate higher initial stiffness and greater ultimate resistance than the closed-ended pipes. In settlement terms, H-piles settle less for a given load, confirming the stiffness advantage in H-piles, while pipe piles exhibit larger displacements prior to peak resistance, reflecting more ductile behavior.

Group effects magnify these differences. The capacities for both pile types are higher in two-pile groups than for singles; however, the gains are not linear. The H-pile groups see a larger percentage improvement, partly because driving multiple open-web sections intensifies sand densification, leading to overlapping stress zones of greater confining pressure between piles.

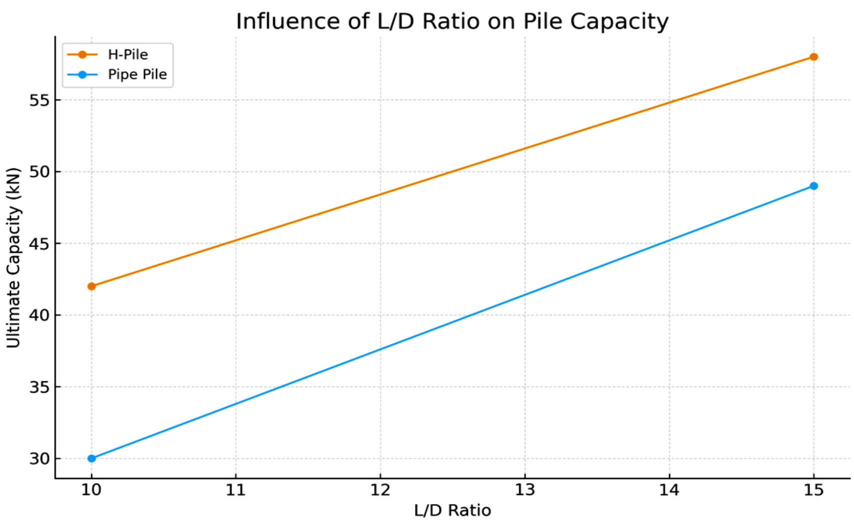

Figure 6: Influence of pile length-to-diameter (L/D) ratio on ultimate bearing capacity for H-piles and closed-ended pipe piles.

Group efficiency for H-pile groups is strikingly above unity and as high as 1.5-1.7, indicative of beneficial densification and particle interlocking developing in this displacement type. Pipe-pile groups develop more modest efficiencies of approximately 1.2-1.3, reflecting a steadier, less aggressive displacement mechanism. Figure **6** illustrates that increased embedment length develops increased axial capacity for both piles, with pipes gaining disproportionately more. Capacity gains measured for fourpile groups are even larger, and the piles still somewhat outperform pipe piles because of better soil plugging, mobilizing shaft friction in more directions, and development of a densified sand block around and between piles. H-pile four-pile groups can develop to as much as about 365% relative to singles, while pipe groups rise around 250-280%, in fundamental consideration of soil-arch and stress-overlap effects that favor the H-piles.

Specific trends in group settlement demonstrate the typical reductions of initial stiffness by group interaction, but with increased loading, the H-pile groups consistently develop a marked recovery in stiffness from the densified block effect, which mobilizes higher shear resistance at lesser settlements. The pipe-pile groups remain softer but nevertheless perform substantially better than singles, in particular at L/D 15. Figure **7** summarizes group efficiency for single, two-pile, and four-pile configurations, with H-pile groups displaying obvious superior performance due to stronger densification and soil arching.

Figure **8's** capacity gain display for multi-pile systems versus single piles shows that H-pile groups realize much greater gains relative to pipe-pile groups. Load-distribution analysis indicates H-piles rely more on shaft friction, whereas pipe piles balance shaft and base resistance more equitably. Post-test inspection verifies that H-piles trap compacted soil within both the flanges and web, confirming strong soil plug formation even though they are not classic tubular piles; this plug substantially increases end resistance and accounts for the unusually high capacities for H-sections. The capacity gain with embedment ratio is quite consistent

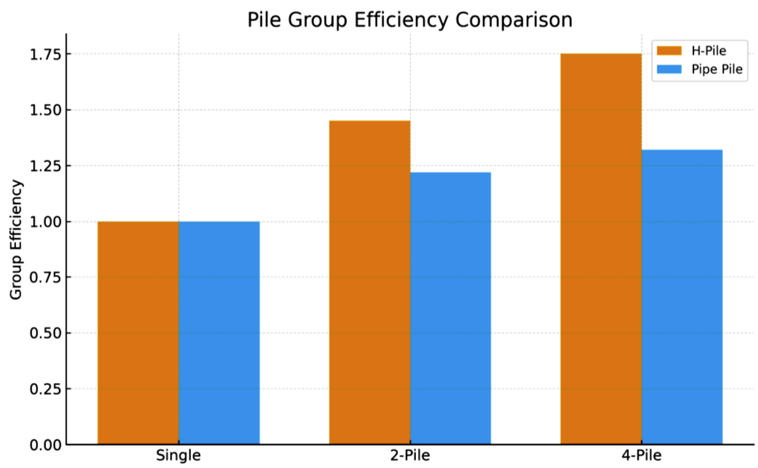

Figure 7: Comparison of group efficiency factors for single, two-pile, and four-pile groups for H-piles and pipe piles.

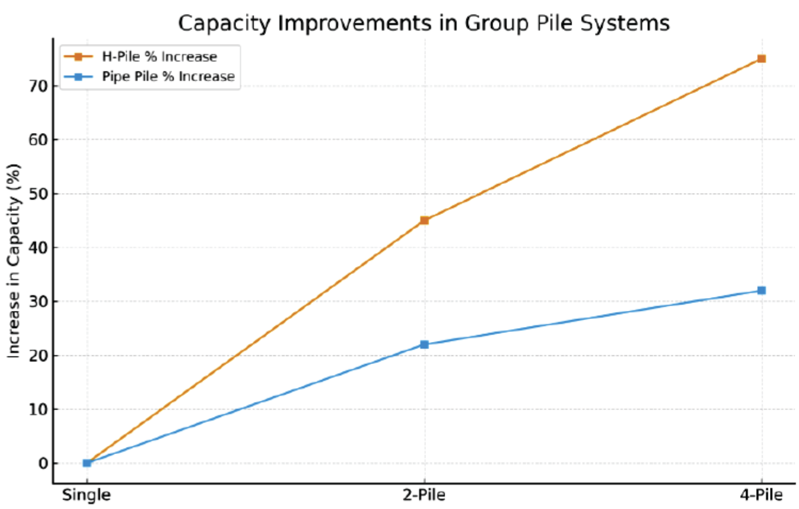

Figure 8: Percentage increase in bearing capacity for two-pile and four-pile groups relative to corresponding single piles.

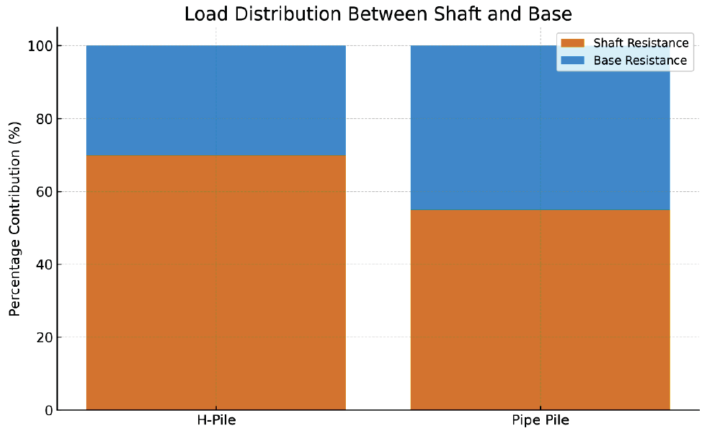

Figure 9: Distribution of load resistance between shaft friction and end-bearing for H-piles and pipe piles.

among all configurations, with L/D = 15 for H-piles giving the greatest improvement owing to the mobilization of internal plug resistance over an extended distance.

Figure **9** presents a comparison of load sharing: the H-piles depend more on shaft friction, while pipe piles distribute more to the action of shaft and base. Driving-induced densification plays a significant role in tests, most especially for groups: the piles driven later develop higher resistances by the formation of the densified sand matrix, improving overall load-carrying behavior. Overall, both the pile configurations tend to perform better with an increase in length and as a group, but the H-section piles consistently outperform the closed-ended pipes in all parameters due to geometric interlock, plug formation, stress concentration, and densification effects. The consistent trends for all embedment ratios and group configurations validate the experimental program and make it a robust dataset for interpretation, model calibration, and eventual development of polymer-enhanced or -coated pile systems based on the mechanical behaviors outlined here.

The findings provide clear insight into the axial behavior mechanisms of both H-section piles and closed tube piles in poorly graded sands, and point to implications for geotechnical practice as well as wider materials and polymer engineering fields, as highlighted within the scope of this journal. The superior performance of H-piles in various configurations is related to plugging inside the open web, improved lateral confinement by densification during driving, and stress concentration along the flange edges. The agglomerate configuration amplifies these effects due to increased sand density and soil compaction between piles, creating an aggregate-like interaction zone that makes load transfer more efficient. These findings are important not only in the quest to understand classical soil-pile interactions, but also to inform the design of future polymer-based pile surface systems, including polymer coatings, FRP wraps, and engineered polymer-soil interfaces. The contrast in shaft-friction-dominant resistance with respect to H-piles and more balanced shaft-base resistance with respect to tubular piles provides a mechanical basis for optimizing polymer-modified pile surfaces to improve friction transfer, control corrosion, or deliver various improvements in terms of long-term durability in granular soils. H-piles can mobilize high resistance at geometrical locks, indicating that controlled roughness, functional groups, or micropatterned textures of polymer coatings are aspects that have the potential to further improve performance, which is relevant to this journal's goal of promoting materials innovation in infrastructure, energy, and transportation applications. The role of induced condensation during installation also points to a potential opportunity for investigation into the development of polymer-based lubricants or mud-stabilizing polymers to control rolling resistance and improve installation efficiency without sacrificing axial capacity. These trends will provide a useful reference for validation against numerical models and constitutive interface laws in simulations using polymer-reinforced piles, particularly at the intersection of geotechnical engineering and composite materials/polymer science. Whereas this study clearly shows the mechanical merits of H-piles, any limitations model-scale piles, single soil type, and monotonic loading undoubtedly indicate future research needs concerning longterm durability, cyclic loading, and interactions in chemically active environments, where advanced polymers have benefits to offer. Future research is expected to be undertaken in relation to functional polymer coatings, FRP jackets, and composite wraps to establish the influence of polymer-modified surfaces on frictional resistance, control of corrosion, fatigue performance, and bonding of soil and pile at both microand macro-scales. Overall, this work presents important experimental evidence in support of geotechnical foundation design and the rising polymer-based innovations aimed at sustainable, high-performance infrastructure systems.

4. CONCLUSIONS

The systematic experimental study of axial performance of H-section steel piles and closed-ended pipe piles in medium-dense poorly graded sand reveals how pile geometry, embedment ratio, and group configuration shape load-bearing behavior. It clearly reflects that H-piles outperform pipe piles under all test conditions due to soil plug formation in the open web, enhanced densification during driving, and effective mobilization of multiaxial shaft friction surfaces. For both types of piles, capacity increases with increasing L/D, although gains are greater for pipe piles since deeper embedment has major effects on the development of shaft friction and end-bearing resistance. Group configuration greatly improves performance, with four-pile H-pile groups realizing the greatest benefits as a result of stress overlap and soil shear acting to create a denser area that acts as a composite block against axial loading. Beyond the basic soil-pile contact, the results provide valuable reference data when designing advanced foundation systems that include polymer coatings, FRP wraps, or engineered polymer-soil interfaces. The advantages of H-piles in achieving wear resistance indicate the potential for layers of functional or specialized polymeric materials, such as textured coatings or corrosion-resistant polymers, to further improve real-world performance. Limitations include model scale, single soil type, and monotonic loading; Potential areas of study are thus cyclic loading, grading variation, long-term durability and pile surfaces treated with polymer modifiers. Overall, this research provides significant experimental evidence to support both geotechnical foundation design and emerging polymer-based innovation toward sustainable high-performance infrastructure.

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