The Behavior of Tapered and Step-Tapered Piles under Lateral Load

Raghavendra HN, Pramodkumar Kappadi, Likhitha H, Arunkumar Yadav.

***Abstract*— The present study is an experimental investigation to determine the behavior of tapered and step-tapered piles in sand (cohesionless soil) under horizontal loads. A series of lateral loading tests were conducted on the modeled tapered and step-tapered piles with varying sections equal to taper angles of 0.5°, 1°, 1.5°, 2°, and segments of 2-segments, 3-segments, and 5-segments respectively. A large experimental facility was established to test the model piles. The testing facility consists of a model steel tank containing soil and a provision for applying an incremental lateral load. The pile was measured along its length to determine its behavior with depth. Tests were performed to failure to investigate the ultimate lateral load capacity and deflection. The results were compared with those of uniform-diameter piles to determine the performance of tapered and stepped piles. The results showed that the lateral capacity of both piles was significantly improved compared with that of the uniform-diameter pile. In addition, it was found that there exists an optimum taper angle and segments for tapered and step-tapered piles, which are in the range of 1° – 1.5° for tapered piles and 3 – 5 segments for step-tapered piles. It was concluded from the study that tapered and step-tapered piles have an increased lateral load-carrying capacity with a better distribution of materials, leading to economic benefits.**

***Index Terms*— tapered pile, step-tapered pile, lateral load, cohesionless soil, deflections**

I. Introduction

THE Piles are typically required to carry axial loads. However, the use of piles to support piers, abutments, transmission towers, offshore structures, and high-rise buildings results in large lateral loads from wind and wave action. Lateral loads can also arise because of artificial causes, such as the impact of berthing on ships; hence, the lateral capacity of piles is important in certain situations. In practice, piles of various cross-sectional shapes, such as round, rectangular, and square piles are often used. The piles used were mostly uniform in cross-section. However, recently, piles with variable cross-sections have been of interest.

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Engineers are currently trying to increase the strength of piles to reduce costs. The increased load-carrying capacity of the pile reduces the required range of the pile. Reducing the number of piles often provides additional financial benefits through the use of smaller pile caps. Increasing the pile capacity requires tougher operations and more efficient equipment. This has created the need for stronger, stiffer, and more reliable piles that are less likely to be damaged during certain stages of pile driving. Therefore, in the present study, piles with greater top cross-sections, tapered piles, and varying cross-sections, that is, step-tapered piles, were the subject of interest.

Over the decades, some studies have focused on the response of uniform diameter piles, with little attention paid to tapered or stepped piles. Most research on tapered and stepped piles focuses on load capacity. [1] conducted the first study on taper piles and investigated their vertical load capacity in sand deposits. [2] conducted model pile load tests to assess the effect of tapered pile shapes with varying cross-sections on ultimate bearing and uplift capacities. The study determined that the tapering angle was a crucial parameter affecting the load capacity of the pile, and concluded that geometrically, triangular piles bore the highest load. [3] and [4] performed experimental field investigations on bored cast-in-situ taper piles.

[5] further emphasized the significance of pile geometry, in which lateral load tests were performed on a series of square and circular short pile models. In single-layer cohesionless soil, [6] discovered that tapered piles can achieve up to 40% higher skin friction than straight-sided wall piles. Their research indicated that the load distribution along the pile shaft for both types follow the same pattern and is influenced by the confining pressure. Moreover, tapered piles are believed to offer greater resistance than straight-sided wall piles. However, it is recommended that tapering be confined to a length equivalent to 20 times the pile diameter. [7] established the response of tapered piles to lateral loads. The bending moment function and the relationship between soil resistance (p) and pile displacement (y) have been developed and have shown that compared to straight wall piles with the same average diameter, conical piles can withstand a horizontal load of up to 77% more. According to [8], test results indicate that the tapering effect is highly advantageous at a depth of approximately 20 pile diameters. The study suggested that increased lateral pressures may lead to reduced shaft resistance coefficient values during compression. [9] conducted extensive tests on large-scale steel piles to determine the behavior of tapered piles under lateral loading. [10] performed loading experiments on sand on straight and stepped piles under axial compressive loads.

The results show that with the same base area as the straight piles, step-tapered piles exhibit high lateral strength with an increased axial load-bearing capacity. [11] studied the load capacity of stepped and tapered piles using FLAC 3D under axial loads. The study revealed that, unlike cylindrical piles, the capacities of both tapered and step piles increased. Furthermore, the difference between the bearing capacities of the stepped piles and fully tapered piles was less than 10%. [12] conducted a parametric study on tapered piles in mudstone by considering the influence of rock strength, surface roughness, taper angle, and length of the pile on lateral resistance development. Based on this numerical study, the main parameters affecting the lateral strength were the surface roughness, rock strength, and taper angle. In addition, in general, in comparison to cylindrical piles, providing a taper to carry an axial load has a significant advantage. A comparative study between conventional pile materials and FRP-reinforced concrete piles on the driving efficiency and static load capacity of piles with tapered geometry was performed by [13]. [14] examined the behavior of step-tapered piles in calcareous sand. A nonlinear response with a significant increase in the lateral load-carrying capacity to the working load and a decrease in deflection was observed for stepped piles. Owing to the strengthening or enlargement of the upper part of the step-tapered pile, the deflection decreases as the load-bearing capacity increases under the effect of a horizontal static load, as observed by [15]. Tapered piles are more suitable as floating pile foundations, as concluded by [16] based on numerical analyses. A numerical investigation using FLAC3D was performed by [17] to contemplate the impact of tapered geometry on the driving of piles based on [18] and [19], which increased the settlement to pile action.

Additionally, [20] tests indicated that the bearing capacity improved with increased volumetric displacement, confining pressure, tapering angle, and driving depth, with tapered piles showing notably higher bearing capacities under elevated confining pressures. [21] investigated the influence of soil setup, variation in concrete modulus, and residual load on tapered instrumented piles in sand. [22] investigated the axial performance of tapered piles under compressive loading by using centrifuge model tests. Their research led to the development of a design approach for tapered piles, recommending that the ratio of the pile top section diameter to its length should be between 20 and 25 for optimal efficiency. However, their tests were limited to small-scale prototype piles with length-to-diameter ratios of 14, 18, and 26, respectively. Additionally, because the models were scaled-down versions of the prototypes, proper field load tests were necessary to verify the optimal efficiency range of the l/d ratio for tapered piles. Further experimental studies by [23] examined the behavior of tapered- and straight-sided wall piles driven into loose sand using centrifuge tests. Their findings indicated that increasing the tapering angle enhanced the shaft resistance, with the shaft bearing capacity of the tapered pile reaching up to 1.85 times that of a comparable straight-sided wall pile. However, they did not specify an upper limit for the tapering angle. They also compared these values with the theoretical calculations by varying the effective overburden pressure. According to [24], the moment distribution diagrams for piles with tapering angles of 0°, 0.53°, 0.71°, and 1.13° show that the maximum moment increases with an increase in vertical/radial confining pressure. The results showed a direct correlation between the maximum moment and the tapering angle. Furthermore, under confining pressures of 30 kPa and 60 kPa, the moment increased by more than 90% as the tapering angle changed from 0° to 1.13°. [25] also discussed this change in moment distribution by testing three different piles with tapering angles of 0°, 0.6°, and 0.95° under static lateral loading conditions. [26] examined the construction and performance of drilled tapered concrete piles in cohesive-frictional soil. Their study demonstrated that tapered piles with tapering angles ranging from 0.96 to 1.92 can offer a load-carrying capacity approximately 1.5 times greater than that of cylindrical piles with the same volume. However, it is important to note that the experimental results were specific to the site where the tests were conducted. [27] discovered that soil load transfer primarily occurs through cylindrical shear failure near the tapered profile. [28] found that the frictional resistance of tapered piles steadily increases with pile settlement. In contrast, straight-sided wall piles reached their maximum frictional resistance at a settlement equivalent to 2% of their diameter. Their study also revealed that the ratio of the load-carrying capacity of tapered and cylindrical piles depends on both the tapering angle and sandy soil conditions. It was suggested that cylindrical piles typically exhibit lower ultimate unit shaft resistance across all sandy soil conditions than tapered piles.

Tests were conducted to investigate the impact of taper angle (0°, 1°, and 1.5°) and soil conditions on the load-bearing capacity of piles [29]. Based on the results of laboratory tests, [30] conducted a study to investigate the relationship between settlement, load capacity, vertical load distribution, skin resistance, and the failure pattern of the pile. The study's results indicate that the proportion of variable diameter influences the performance of the pile. [31] found that as the taper angle increases, the settlement of the pile decreases. Furthermore, the load-deflection curve demonstrates that a pile with a taper can withstand greater loads than a cylindrical pile when the taper angle is above 0.5°. In their study, [32] examined the comparative behavior of tapered and uniform piles driven in loose sands and discussed the reliability of N (bearing capacity factor) and Kh (coefficient of lateral earth pressure) values. [33] evaluated frictional resistance through the lens of cavity expansion theory and the stress-dilatancy relationship. Furthermore, they assessed the point resistance of tapered piles by defining a taper coefficient. Their experimental findings indicated that a modest increase in the tapering angle results in increased skin resistance and exerts influence on the point-bearing capacity, relative to conventional cylindrical piles in diverse sands and relative densities Tapered piles show a stiffer response to lateral displacement based on a parametric numerical study of the bending behavior of tapered piles under lateral loading in cohesive soils conducted by [34]. [35] conducted numerical and experimental examinations on the drivability behavior of tubular piles with distinctive forms and demonstrated superior drivability performance with lower energy utilization for tapered piles compared with solid concrete piles of the same volume and length. In a study conducted by [36], it was determined that the tapered design of piles results in the compaction of the surrounding soil during the driving process. This compaction can result in an increased lateral earth pressure coefficient in the surrounding soil. [37] investigated the axial capacity of tapered spun-cast ductile iron (SCDI) piles with a lower helical plate. A three-dimensional finite element analysis was conducted to evaluate the axial performance of the system. The findings indicated that tapered helical piles demonstrated a more rigid response and achieved higher capacities than straight-sided piles. Additionally, [38] observed that as the tapering angle increased, particularly under axial vibration loading conditions, the resonant amplitude of tapered piles decreased. This advantage renders tapered piles more advantageous for dynamic design applications.

By the principles of expansion cavity theory and wave equation analysis, tapered piles are more readily driven in cohesive soil than uniform diameter piles of equivalent length and volume, [39]. Additionally, based on field and numerical studies, [40] concluded that the implementation of piles with tapered profiles resulted in a reduction in ground vibration, consequently leading to a diminished noise level. Concerning the load transfer mechanism, a theoretical model was proposed by [41] for step-tapered hollow piles. A numerical study on step-tapered piles under horizontal and vertical loads was conducted by [42]. A study published in [43] investigated the drivability of offshore tapered and stepped-tapered piles subjected to hammer blows with the same volume and length. In their study, [44] employed FLAC 3D to demonstrate that an increase in the shear strength parameters resulted in an enhanced load capacity for the stepped pile, which was thus deemed suitable for use in hard strata. Moreover, [45] conducted a numerical and experimental investigation into the load-carrying capacity of groups of tapered and cylindrical piles. The study concluded that a minimum spacing for tapered piles should be significantly greater than that for uniform piles, with a minimum spacing of 3D being proposed. The drivability performance of offshore tapered and stepped piles of the same volume and length under the action of hammer blows has been investigated by [46]. The impact of tapered and semi-tapered configurations on the drivability of offshore piles was examined by [47] through a combination of field testing and numerical analysis. Their findings indicated that tapered geometry offers a distinct advantage in terms of enhanced performance, necessitating fewer blow counts to achieve penetration than cylindrical piles. This translates to reduced energy expenditure. To illustrate the outcomes derived from both field experimentation and numerical techniques, the pile-driving process is analyzed and discussed in the context of the wave propagation mechanism. The study reveals that tapered piles exhibit enhanced performance in pile driving and for simulating pile drivability, where simple one-dimensional numerical methods can be effectively employed. [48] employed analytical solutions to investigate the impact of pile and foundation soil properties on the lateral vibration characteristics of a tapered pile in an arbitrarily layered soil system. In a study conducted by [49], the performance of straight and tapered pile groups in sand deposits with circular, square, and X-shaped cross-sections was examined under axial compressive load using a centrifuge. The findings indicated that the tapered pile group exhibited a greater tolerance to axial load and stiffness, with an increase of approximately 20% in axial load and 35% in stiffness, respectively, compared to the straight pile group. Additionally, the tapered pile group demonstrated a reduced settlement compared to the straight pile group. In contrast, the behavior of laterally loaded piles has been examined based on the elasticity theory put forth by [50], [51], [52], and [53]. While [53] and [54] proposed modifications incorporating yield factors to account for soil non-linearity, they did not consider the effect of the tapering angle in their models. The inclined body of tapered piles can affect the lateral earth pressure coefficient by mobilizing a portion of passive pressure (Kp), subsequently impacting lateral performance.

Conversely, a substantial body of theoretical research has been conducted, including the development of models to investigate the dynamic axial and lateral behavior of piles with non-uniform cross-sections. Prominent examples include the work of [55], [56], and [57] [58] [59]. In addition, the following authors have made significant contributions to this field: [60], [61], [62] [63] [64]. In some of these theoretical models, [65] incorporated geometric damping, which represents a primary form of energy dissipation associated with the deformed surface area during wave propagation. Other studies have excluded material damping, which, according to [55] and [56], can impact the dynamic response of piles. Among the models proposed for analyzing the dynamic response of tapered piles, [66] developed a continuum method based on the elasto-dynamic theory proposed by [65], [67], utilizing a segment-by-segment (SSM) approach. [68] reviewed that the most significant parameter that affects the reaction of tapered piles to static and impact loads is the taper angle. A constant resonant frequency with a decrease in resonant amplitude, more stiffness, and a lesser amount of damping was increased angle of taper. [69] investigated the negative skin friction of single and group tapered piles. The investigation also involved the effect of taper angle on neutral plane depth. The results showed that although tapered piles are economically advantageous for both single and group piles, they can increase NSF by up to 46.7% for individual piles and up to 28.1% for group piles.

Only a limited number of tests were conducted on the piles, with the majority focused on numerical analyses. The majority of previous research has focused on the vertical capacity of homogeneous soil layers with varying degrees of density and pile geometry. Given the limited understanding of the behavior of these piles under lateral loads, it is crucial to gain insight into their lateral behavior for the design and stability of structures subjected to lateral forces, such as wind, waves, and seismic activities. This study provides insights into the advantages of tapered and step-tapered piles in terms of load-bearing capacity, deformation characteristics, and overall performance under lateral loads.

II. Experimental Preparation

This section presents and discusses the materials required for the present experimental investigation, including the soil medium, model piles, and testing facility.

A. Soil sample

In the present experimental study, locally available river sand, Figure 1 in dry conditions was considered as a soil/foundation medium. The properties of the sand were determined by subjecting it to various laboratory tests as per the respective ASTM Standards. The sand is of sub-granular particles and was classified as Poorly Graded (SP) as per the Unified Soil Classification System. The coefficient of curvature and uniformity are 0.89 and 3.2 respectively. Other properties of the sand are presented in Table 1.

TABLE I
PROPERTIES OF SOIL SAMPLE

Properties		Value
Specific gravity		2.64
Effective particle size, D10 (mm)		0.5
D30 & D60 (mm)		0.7 & 1.1
Uniformity coefficient, C_u		3.2
Coefficient of curvature, C_c		0.89
Classification (ASTM D2487-11)		Poorly graded sand
Unit weight (kN/m^3)	Max	16.19 (e_{min} = 0.62)
	Min	13.63 (e_{max} = 0.9)
Friction angle (degree)	Loose	28^0
	Dense	39^0

Fig. 1. Soil sample in the present study

The tests were performed in two different soil conditions, ie; loose and dense states. The placement density for loose sand and dense sand state was 14.323 kN/m^3 and 15.313 kN/m^3 respectively. The sand was prepared by 500 mm and 100 mm freefall for dense and loose conditions respectively, using the rainfall technique.

B. Model Piles

To constitute the prototype pile, model piles made of aluminum were selected based on the similitude law proposed by [69]. The present experimental study adopted two different scale systems for tapered and step-tapered piles. A length scaling factor of 1/20 and 1/18 is adopted for tapered and step-tapered piles respectively. This simulates a prototype tubular pile 12 m long, 0.6 m diameter, and made of steel with Young's modulus E = 210 GPa. Two methods are available for the production of a tapered pile. One method is to increase the butt diameter while maintaining a constant tip diameter, thereby producing tapered piles with varying taper angles. These piles are then compared with a corresponding uniform-diameter pile, which has the same volume as the tapered pile. The latter method entails modifying both the butt and tip diameter of piles to create a volume-equivalent cylindrical pile with a taper angle distinct from that of the original. To create a stepped pile, the pile is divided into segments of an appropriate length with a constant diameter, the total circumference of which is equal to that of the reference cylindrical pile. Figure 2 illustrates a schematic representation of tapered and step-tapered piles. Tables 2 and 3 present the dimensions of the model piles, while Figure 3 depicts a scaled model of step-tapered and tapered piles.

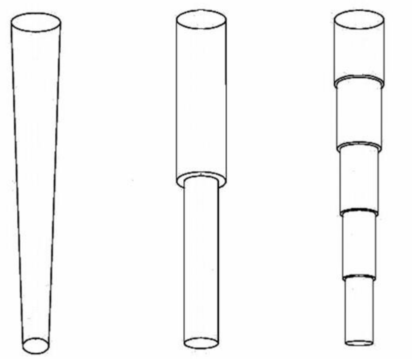


Fig. 2. Schematic representation of taper and step-tapered piles

TABLE 2
PILE WITH DIFFERENT TIP DIAMETERS

Taper angle (α)		Diameter (mm) Tip	Diameter (mm) Butt	Volume ($x10^{-4}$, m^3)
0	S	30	30	4.24
0.5	T1	25	35	4.24
1.0	T2	21	38	4.24
1.5	T3	16	42	4.24
2.0	T4	12	45	4.24

TABLE 3
PILE WITH VARIABLE SEGMENTS

Number of segments		Length of each segment (mm)	Diameter of each segment (mm)	% Increase in diameter
0	S1	650	27.00	0
2	P1	325	40.00	48
			27.00	0
3	P2	216.67	40.00	24
			33.50	24
			27.00	0
5	P3	130	40.00	48
			36.75	36
			33.50	24
			30.25	12
			27.00	0
0	S2	650	40.00	48

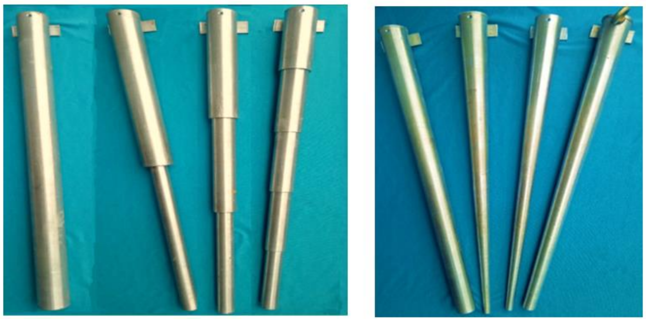


Fig. 3. Model step-taper and tapered piles

The length of the model tapered piles was 600 mm long and that of step tapered piles was 650 mm long respectively. The piles were categorized as short rigid piles since their length is less than 2T, where T is the characteristic length [71] and is given by $\sqrt[5]{\frac{E_p I_p}{n_h}}$, where E_p is elasticity modulus of pile material, I_p is the moment of inertia of the pile section, n_h is constant of subgrade reaction modulus.

C. *Testing Tank*

A large rigid model testing tank of size 1.2 m wide and depth of 1.5 m, made of steel was selected. The tank wall is 10 mm thick and is equipped with a manual winch to apply the load. In addition, the tank had a provision for the dial gauges along the depth to measure the pile deflections during the load testing.

III. Test Setup and Procedure

Most experiments on small-scale model tests involving tapered piles utilized a chamber apparatus and the pluviation technique, with steel pipes as the pile material. In the air-pluviation technique, dry sand particles are poured into the chamber through the air from a specific height at a constant velocity [72]. The relative density is a principal condition parameter that affects the behavior of sand. For relatively large laboratory tests, the preparation of sand samples with a uniform density is essential. Various methods such as vibration, pluviation, tamping, etc. are available to establish the state of sandy soils in the laboratory. Among all, the pluviation/raining technique is preferred mostly since it produces moderately uniform specimens and replicates similar soil fabric as the process of natural deposition of sands.

For this, a cylinder of known volume and weight is taken and located at the bottom of the tank. Initially, the raining mesh is placed over the cylinder at a particular trial height. From the particular trial height, the sand is allowed to free-fall to achieve reproducible density. After absolutely filling the cylinder, the weight is measured, and density is determined. The procedure is repeated by changing the height of the raining platform and the corresponding densities of sand are determined. Figure 4 shows the schematic view of an experimental setup. First, the raining deck or platform was placed straight over the model testing tank at the desired height to achieve the required sand density. After the sand surface is leveled to the height of the pile base, the pile is positioned 200 mm from the back portion of the tank to mitigate edge effects, held upright with a clamp, and then the next layer of sand is added. The raining deck's position is adjusted every 10 cm fall to maintain a consistent fall height, ensuring the specified relative density of the sand is achieved. Once the tank is filled with sand to the upper level, a flexible wire of smaller diameter is attached to the pile head and connected to a manual hand winch assembly. Dial gauges are placed along the entire pile length and adjusted to zero transverse displacements to measure deflection.

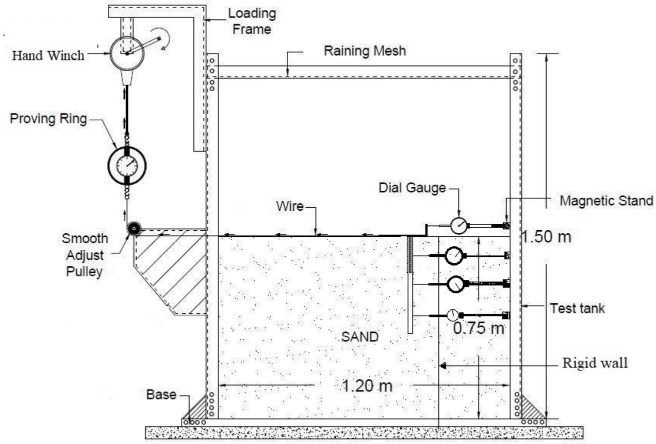


Fig. 4. Representation view of the experimental setup

Loads are applied incrementally to the pile head, and the corresponding displacements are recorded. The test continues until the load stabilizes or decreases to a minimum displacement of 25 mm. The tests are repeated with piles of different taper sections and segments. Load versus displacement diagrams are plotted, and the bearing capacities of the piles are determined. For each test demonstration, the soil is removed from the tank and replaced to the desired density and thickness.

IV. RESULTS

A sequence of load tests was performed on the model instrumented piles to know the influence of different parameters such as soil density, taper angles, and number of segments on the performance of straight, tapered, and stepped piles. The following section describes the load-displacement graphs that were plotted for the performed loading tests. Figure 5 presents the pile's position before and after the application of lateral load.

Fig. 5. Initial and final position of pile head

A. *Pile-head deflection.*

Figure 6 illustrates the correlation between load (N) and deflection (mm) for taper piles subjected to lateral loads in a loose sand deposit. The cylindrical pile (S) demonstrates the lowest load-bearing capacity for a given deflection, indicating a comparatively lower resistance to lateral loads in comparison to taper piles. Pile T1, with a 0.5° taper angle, demonstrated a notable enhancement in load-bearing capacity in comparison to the pile S. The increase in taper angle from 0° to 0.5° resulted in augmented lateral resistance, as evidenced by the elevated load values at corresponding deflections. Pile T2, with a 1.0° taper angle, demonstrated a further enhancement in load-bearing capacity. At the same deflection levels as the pile S and T1, pile T2 exhibited significantly higher loads. Piles T3 and T4, with a taper angle of 1.5° and 2°, respectively, demonstrate a continuation of the observed trend of increasing load capacity with increasing taper angle. However, it is notable that the load values for T4 are the highest at any given deflection, indicating that the 2.0° taper angle provides the most substantial increase in lateral resistance compared to other taper angles.

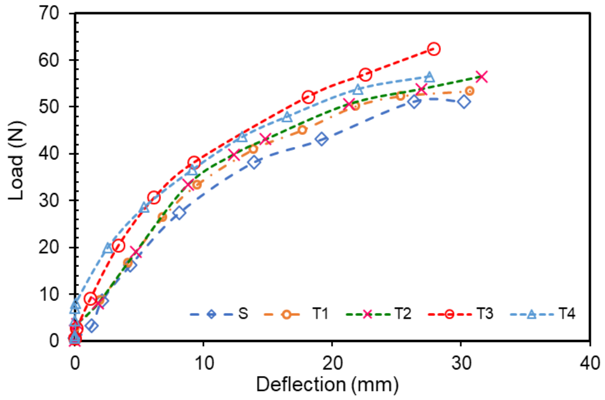


Fig. 6. Load-deflection curve of tapered piles in loose sand.

The observed behavior can be attributed to the geometry of the taper piles. An increase in taper angle results in an enhancement of the pile's lateral resistance, which is attributed to an improvement in the interaction between the pile and the surrounding sand. A larger taper angle creates a larger surface area, which enhances frictional resistance and facilitates the more effective distribution of the load along the length of the pile. Furthermore, the tapered shape may induce a wedging effect in the sand, thereby enhancing lateral load resistance. As the taper angle increases from 0° to 2.0°, the lateral resistance also increases, as evidenced by the load-deflection curves. Therefore, taper piles are more effective in resisting lateral loads in loose sand conditions, with higher taper angles offering superior performance.

The behavior of straight and tapered piles in dense sand deposits is illustrated in Figure 7. Pile S demonstrates the lowest load-bearing capacity for a given deflection in the dense sand deposit, a pattern that is analogous to that observed in loose sand. The load values for the straight pile exhibited an increase in deflection; however, they remained significantly lower than those for the tapered piles, indicating a reduction in lateral resistance. Pile T1, with a 0.5° taper angle, exhibited a discernible enhancement in load-bearing capacity relative to pile S. The increase in the load with deflection was more pronounced, indicating that even a modest taper augments lateral resistance in dense sand. Pile T2, with a 1.0° taper angle, continues to demonstrate an enhanced load-bearing capacity. The load values for T2 are consistently higher than those for T1, indicating that a 1.0° taper angle provides superior lateral resistance in dense sand compared to a 0.5° taper. This trend of increased load capacity with increased taper angle is observed only up to a taper angle of 1.0°. Furthermore, an increase in the taper angle from 1.0° to 2° has no significant impact on the lateral deflection.

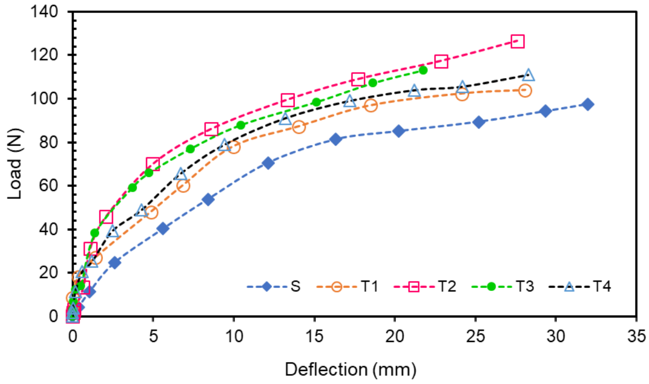


Fig. 7. Load-deflection curve of tapered piles in dense sand.

In conditions of dense sand, the lateral resistance of piles is typically elevated due to the augmented confining pressure and frictional resistance provided by the denser soil particles. The geometry of taper piles serves to enhance this effect by increasing the surface area in contact with the soil, thereby improving the frictional resistance and load distribution. As the taper angle increases, the lateral resistance of the pile also increases due to the larger surface area and the potential for a wedging effect in the dense sand. The taper angle helps to mobilize more soil resistance, resulting in higher load-bearing capacities for taper piles compared to straight piles.

Figure 8 illustrates the correlation between the load (N) and deflection (mm) for diverse pile types subjected to lateral loading in loose sand. The pile configurations under consideration include straight piles (S1 and S2) and stepped piles (P1, P2, and P3) with varying segments. Pile S1, with a diameter of 27mm, demonstrates the lowest load-bearing capacity and the highest deflection for the same applied loads. While S2 demonstrated superior resistance compared to S1, it still exhibited lower resistance than the stepped piles. A reduction in diameter results in a diminished surface area in contact with the soil, thereby providing less resistance to lateral loads. Consequently, it exhibits greater deflection under lower loads, rendering it the least stiff and least effective among the pile configurations.

The P1 pile displays an intermediate load-deflection behavior, exhibiting a higher load-bearing capacity than the S2 pile but a lower capacity than the P2 and P3 piles. The two-segment stepped taper design offers a modest enhancement in stiffness and load-bearing capacity relative to the straight piles S1 and S2. The step effect facilitates the more effective distribution of lateral loads, which in turn reduces deflection. However, this effect is not as pronounced as in the more segmented piles, P2 and P3. The three-segment taper is more effective than the P1 configuration in distributing lateral loads. The P3 pile demonstrates the most optimal performance, exhibiting superior stiffness and load-bearing capacity in comparison to P1 and P2. The five-segment taper pile exhibits an even more effective distribution of lateral loads, which results in a reduced deflection and increased load-bearing capacity. The augmented number of segments facilitates the optimization of stress distribution along the pile, thereby rendering it the most effective taper pile configuration within the context of this study.

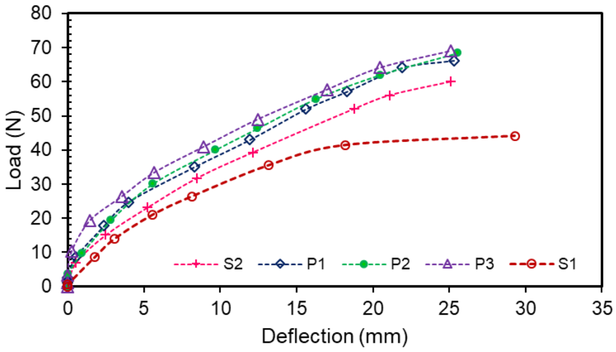


Fig. 8. Load-deflection curve of step-tapered piles in loose sand

From Figure 9, it can be seen that various pile configurations under lateral loading in a dense sand deposit reveal that stepped taper piles generally demonstrate superior load-bearing capacity and resistance to deflection when compared to straight piles. The straight pile S2 (42mm dia) demonstrates satisfactory performance but is outperformed by the stepped taper piles, particularly the three-segment pile (P2), which exhibits the highest load-bearing capacity with minimal deflection. The smallest straight pile (S1, 27mm dia) exhibits the lowest load-bearing capacity and the highest deflection, indicating a reduction in stiffness and effectiveness. Among the stepped taper piles, P2 demonstrates the optimal balance in load distribution, thereby achieving the greatest efficiency. P3 (five segments) and P1 (two segments) also exhibit strong performance, with P3 exhibiting slightly lower efficiency than P2 but still superior to S1. In general, the stepped taper design, especially with three segments, is the most effective method of utilizing the properties of dense sand to resist lateral forces.

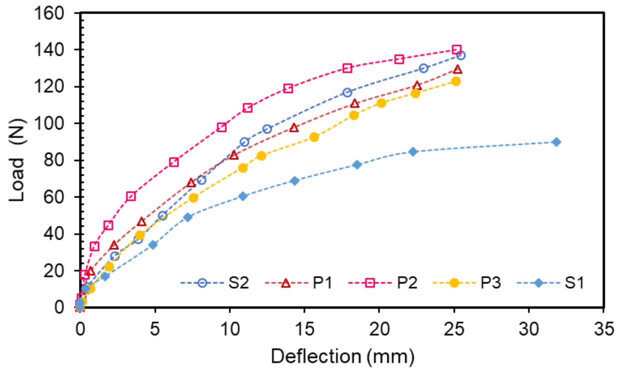


Fig. 9. Load-deflection curve of step-tapered piles in dense sand

B. *Ultimate load capacity*

The ultimate lateral bearing capacity of the pile is determined based on the allowable criteria for the pile's horizontal displacement. In the absence of a failure criterion for determining the ultimate lateral load capacity, as proposed by Prakash and Sharma, the ultimate load is considered for a corresponding lateral displacement of 6.25 mm.

Figure 10 illustrates the ultimate lateral load of the pile in loose sand conditions for tapered piles, corresponding to a 6.25 mm lateral displacement. As illustrated in the figure, the tapered pile with a taper angle of 2°, T4, and 1.5°, T3, exhibited a higher ultimate value than the pile with a taper angle of 1°, T2, and in turn than the pile with a taper angle of 0.5°, T1. Additionally, an increase in taper angle from 1° to 1.5° resulted in a significant rise in ultimate load, reaching approximately 20%. Nevertheless, the ultimate values for piles T3 and T4 are comparable. Figure 11 illustrates that tapered piles exhibit a greater ultimate value than their straight counterparts in dense sand conditions. As the angle of the taper increases, the load-carrying capacity also increases. However, this increase in ultimate load is limited to a taper angle of 1.5°, T3, beyond which there is no additional beneficial effect of increasing the angle.

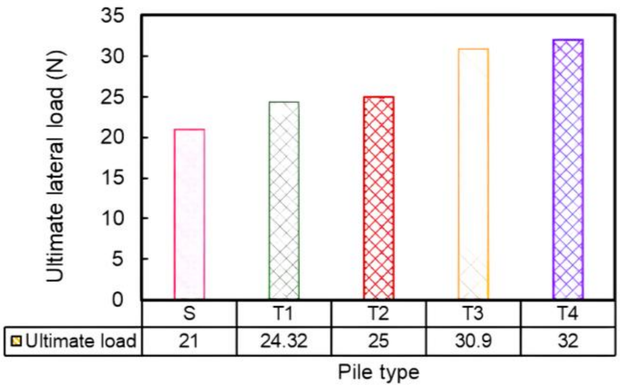


Fig. 10. Ultimate lateral load of tapered piles in loose sand

Figures 12 and 13 illustrate the ultimate load for step-tapered piles in loose and dense sand, respectively. In the loose sand condition, the pile with two segments (P1) exhibited a 40% greater load-bearing capacity than the straight pile (S1).

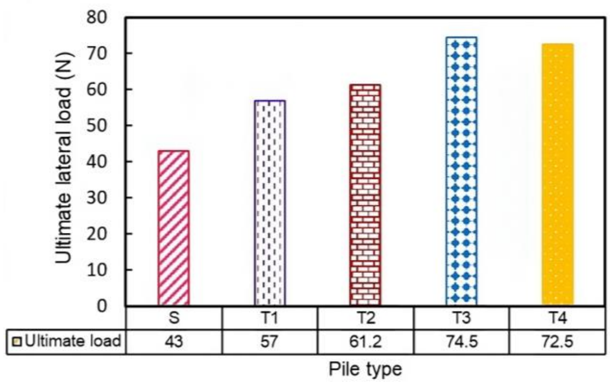


Fig. 11. Ultimate lateral load of tapered piles in dense sand.

Additionally, it can be observed that the pile with three segments, P2, exhibited a relatively minor increase in load capacity. Pile P3 exhibited a 2% increase in load capacity relative to P2. However, the situation differed for the pile with five segments, P3, which exhibited a greater ultimate load than all other piles.

In conditions of dense sand, the ultimate load of the piles was found to exceed that of piles in loose sand. The pile comprising three segments exhibited a greater ultimate load than any other pile. However, the pile with five segments designated P3 demonstrated a reduction in ultimate load-carrying capacity relative to P1, P2, and consequently, S2.

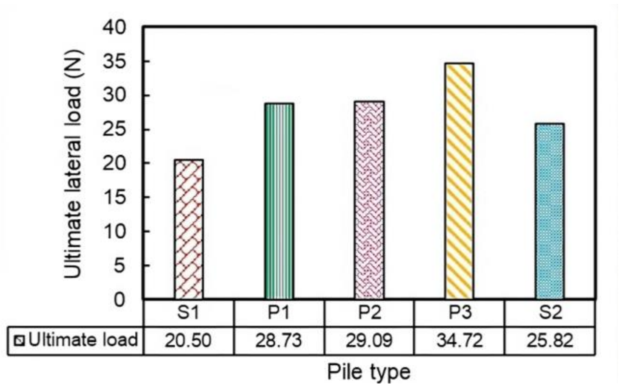


Fig. 12. Ultimate lateral load of step-tapered piles in loose sand

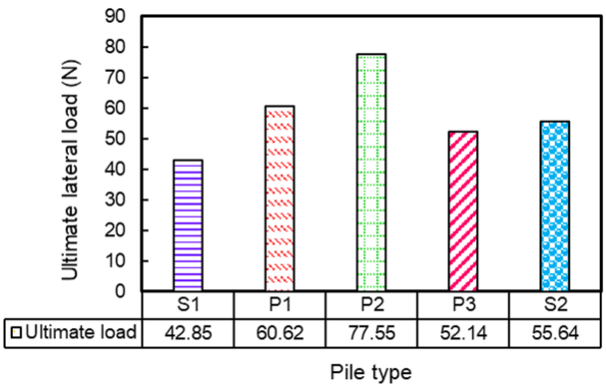


Fig. 13. Ultimate lateral load of step-tapered piles in dense sand

C. *Pile Deflection*

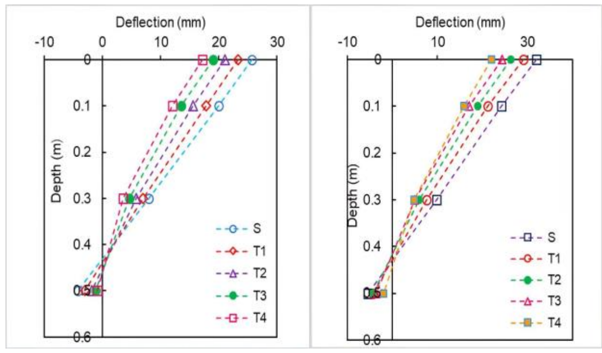
The pile deflection for tapered piles under the lateral loads in different densities of soil is shown in Figure 14.

Following the prevailing conditions, the displacement is contingent upon the load, with a value of 52 N in loose sand and 97 N in dense sand. As illustrated in the figure, the lateral deflections exhibited a pronounced decline with an increase in the angle of taper for the pile. The tapered piles exhibited reduced deflections along the axis in comparison to the straight piles at equivalent load values. The deflection of the pile in response to lateral loads is greatest at the pile head and decreases significantly along the length of the pile. Moreover, in the context of tapered piles, the unit friction exceeds that observed in straight piles along the shaft. Therefore, tapered piles exhibit reduced deflection along the shaft. However, pile T4 exhibited greater stiffness due to the closer proximity of the pivot point to the pile tip.

Figure 15 illustrates the deflected shapes of step-tapered piles in relatively loose and dense sand cases, respectively. It can be observed that the deflection along with the depth for stepped piles is significantly reduced in comparison to uniform piles. In relatively dense sand conditions, step-tapered piles exhibited rigid behavior, thereby reducing the pile deflection to the lateral loads.

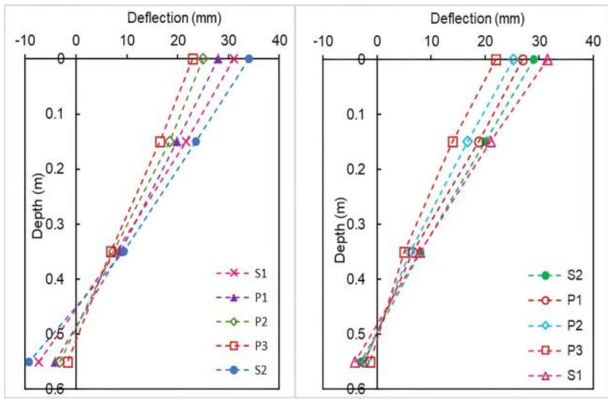
D. *Bending Moment*

The bending moment along the pile shaft was determined similar to the approach developed by [6]. The maximum bending moment for all piles was observed at approximately 1/3 of the pile and exhibited a gradual decline with depth at a load of 52 N and 97 N in loose and dense sand respectively.



(a) Loose sand (b) Dense sand

Fig. 14. Deflection of tapered piles along the length



(a) Loose sand (b) Dense sand

Fig. 15. Deflection of step-tapered piles along the length

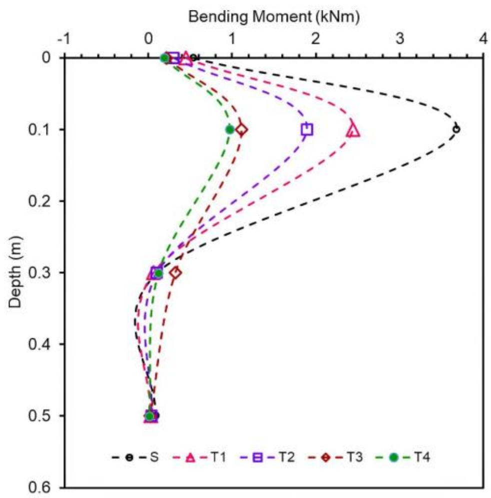


Fig. 16. Bending moment of tapered piles in loose sand

Figure 16 clearly shows that the straight pile exhibited considerable bending stresses at the same lateral load intensity. The pile T1 demonstrated a decline in bending moments in comparison to the uniform diameter pile. The peak bending moment for T1 is marginally inferior to that of the straight pile, and the moment exhibits a more gradual decrease with depth in comparison to the straight pile. The reduction in bending moment with depth is more pronounced for T2. The bending moments for T3 are distributed more evenly along the pile length and for T4 the moments decrease steadily with depth, and the profile is relatively uniform.

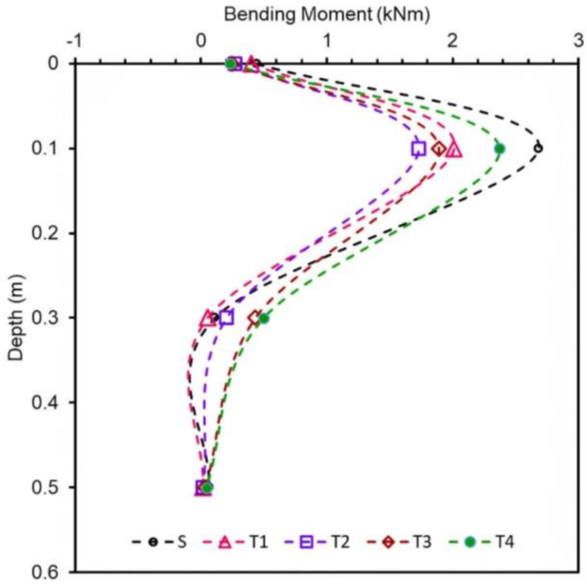


Fig. 17. Bending moment of tapered piles in dense sand

Figure 17 illustrates the bending moment of tapered and uniform-diameter piles in dense sand deposits. The straight pile (S) exhibits the highest bending moment values, particularly at shallower depths. However, a notable decline in bending moment is observed for T1, indicating an enhanced yet still considerable bending stress concentration. The bending moment profile is relatively smooth, exhibiting a gradual decrease from the pile head to the tip for T3 and T4, respectively.

The observed bending moment profiles can be attributed to the differences in geometry and structural behavior between the straight and taper piles. As the taper angle increases, the cross-sectional area of the pile also increases. This results in a pile with greater stiffness, which is better able to resist bending forces. Moreover, an increase in the taper angle results in a higher moment of inertia, which consequently reduces the bending moments experienced by the pile. This explains the progressive decrease in bending moments from T1 to T4. Furthermore, the interaction between the soil and the pile is of paramount importance in determining the pile's bending behavior in dense sand. The varying cross-sectional geometries of taper piles facilitate more efficient engagement with the surrounding soil, thereby providing enhanced lateral support. The enhanced soil-pile interaction observed in taper piles leads to a reduction in bending moments and a more uniform stress distribution along the pile length.

The bending moment profiles, Figure 18, of various pile types under a lateral load in loose sand exhibit distinct patterns, which are influenced by the diameter of the pile and the configuration of the segments. The uniform diameter pile S1 exhibits high bending moments in the near-surface region, with a gradual decrease with depth. This indicates that higher stress concentrations are present at shallow depths due to the smaller diameter of the pile. In contrast, the larger-diameter uniform pile S2 exhibits lower bending moments and a more gradual decrease, reflecting its enhanced resistance to bending. The performance of stepped piles is demonstrably superior. Pile P1 displays lower overall bending moments than S1 but higher than S2, with peaks occurring at the segment transitions. Pile P2 exhibits a more uniform profile with reduced peak values, indicating more optimal stress distribution. Pile P3 demonstrates the most effective resistance, exhibiting the lowest bending moments and a notably smooth profile. This indicates that an increased number of segments leads to enhanced stress distribution and a reduction in bending moments. These observations indicate that larger diameters and increased segment counts enhance bending resistance and stress distribution, which is of particular importance in loose sand conditions where soil provides minimal lateral support.

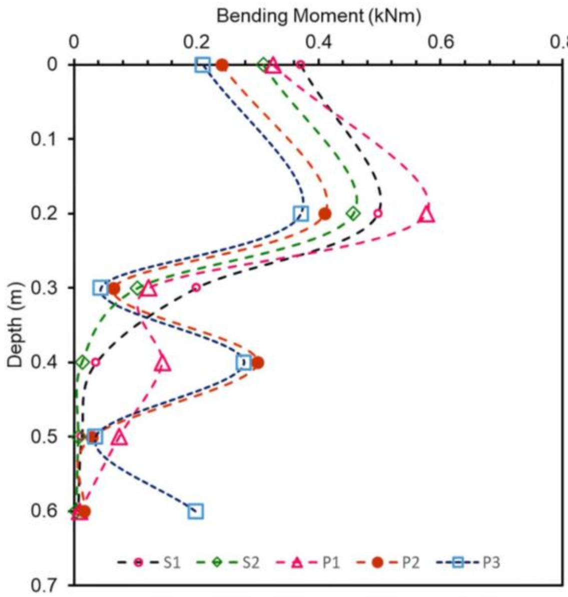


Fig. 18. Bending moment of stepped piles in loose sand

Figure 19 depicts bending moment distributions for various pile types under a 97 N lateral load in dense sand revealing distinct performance patterns. The uniform diameter pile S1 (27 mm) demonstrates the lowest bending moments, which is indicative of its limited stiffness and capacity to resist lateral forces due to its smaller diameter. In contrast, the larger diameter pile S2 (42 mm) demonstrates higher bending moments, with a peak at greater depths, indicating enhanced resistance and stiffness. The stepped piles demonstrate a progressive enhancement in performance. P1 (2 segments) demonstrates intermediate bending moments, benefiting from its stepped design but not to the extent observed in piles with a greater number of segments. Pile 2 (3 segments) exhibits significantly higher bending moments and superior load distribution compared to Pile 1. Pile 3 (5 segments) demonstrates the highest bending moments, with a pronounced peak at greater depths, due to its optimized segment configuration that enhances load distribution and stiffness.

E. Soil Reaction

The soil resistance along the pile shaft was assessed using bending moment values through a method similar to that proposed by Matlock and Ripperger (1956).

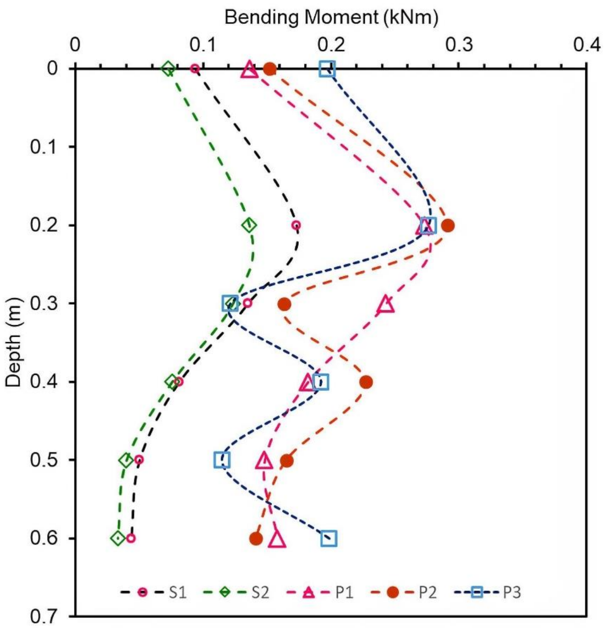


Fig. 19. Bending moment of stepped piles in dense sand

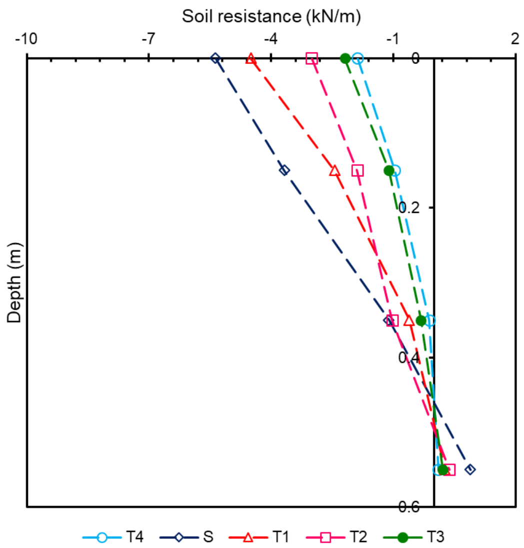


Fig. 20. Soil reaction of tapered piles in loose sand

Figure 20 shows the variation of soil reaction along the depth of tapered piles in loose sand deposits. The tapered piles (T1 to T4) with progressively larger taper angles (from 0.5 to 2°) show higher soil resistance at shallow depths compared to the straight pile. This can be attributed to the increase in diameter along the depth of tapered piles, which increases the contact area with the surrounding soil. A larger surface area enhances the passive resistance developed in response to lateral loads, resulting in greater soil resistance values for piles with steeper taper angles. This effect is most pronounced for the T4 pile, which has the highest taper angle, 2°, yielding the highest soil resistance at similar depths compared to other configurations.

Furthermore, as the depth increases, soil resistance values tend to decrease for all configurations. This reduction could be due to the reduction in bending moments at greater depths, which lowers the load transfer to the surrounding soil. Additionally, the impact of tapering becomes less significant at deeper depths, where the pile diameter approaches its base dimension, reducing the differential effect between tapered and straight piles.

For the dense sand case, as illustrated in Figure 21, soil resistance generally increases across all pile types compared to the loose sand case. The effect of tapering is also more pronounced in dense sand, with tapered piles (T1-T4) showing progressively higher soil resistance as the taper angle increases from 0.5 to 2°. Tapered piles have an increased surface area along their length, allowing more

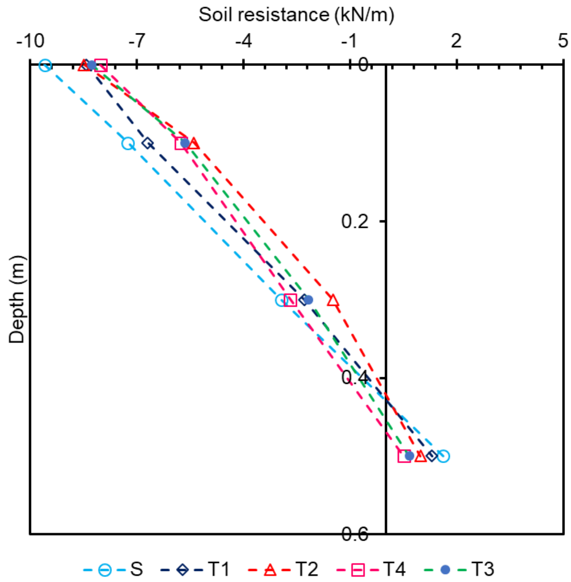


Fig. 21. Soil reaction of tapered piles in dense sand

interaction with the dense sand matrix. This results in higher passive resistance compared to straight piles, particularly near the shallow depth where the diameter increase is more significant. Pile T4, with the highest taper angle of 2°, experiences the greatest soil resistance at similar depths, benefiting from both the high density of the sand and the enhanced surface contact due to its taper.

As depth increases, soil resistance generally decreases for all pile types in dense sand, though it does so at a slower rate than in loose sand. The denser sand provides greater confinement and frictional resistance along the pile length, which retains a higher soil reaction as depth increases. This indicates that dense sand is more effective at maintaining lateral resistance at greater depths compared to loose sand, where resistance diminishes more sharply with depth.

Figure 22 illustrates that the soil resistance decreases more rapidly with depth across all pile types, a characteristic associated with the low confining pressure and lower frictional resistance in loose sands. The straight piles, S1 and S2 exhibit less variation in soil resistance along the depth compared to the stepped piles, P1, P2, and P3. This behavior can be attributed to the uniform diameter of straight piles, which limits the lateral confinement and surface area interaction with the surrounding sand.
For the step-tapered piles, soil resistance generally increases as the number of segments increases. Pile P3 showed the highest soil resistance values among the step-tapered piles, while pile P1 exhibited the lowest. This trend is primarily due to the increased surface area and change in diameter along the length of the pile, which enhances passive

resistance. Each transition or step in diameter creates an additional interface that interacts with the surrounding sand, increasing soil confinement and, consequently, resistance. This effect is cumulative in the P2 and P3 piles, which have more steps and therefore generate higher resistance.

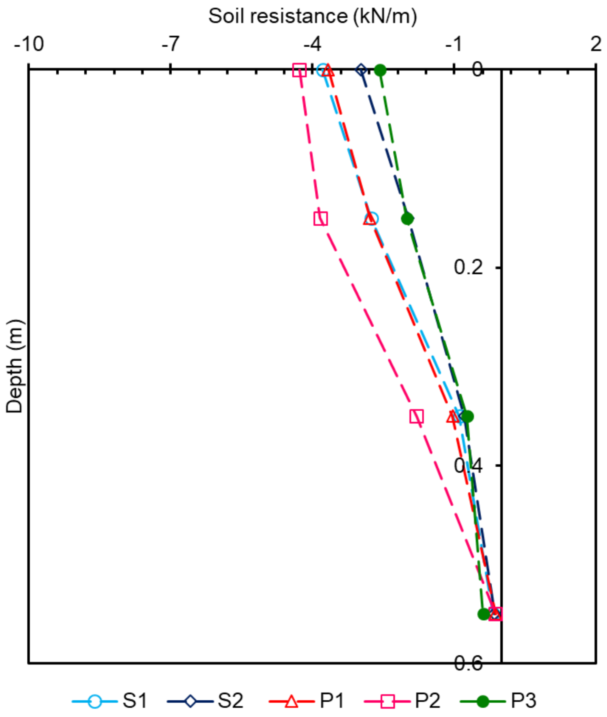


Fig. 22. Soil reaction of stepped piles in loose sand

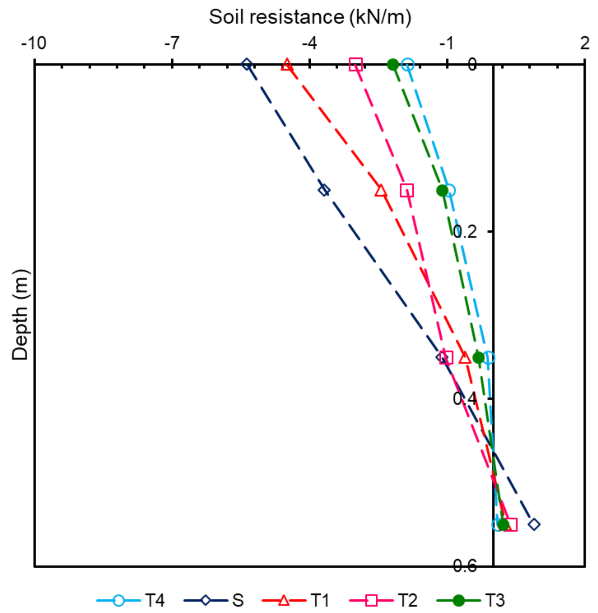


Fig. 23. Soil reaction of stepped piles in dense sand

Figure 23 illustrates soil resistance with depth for piles of varying diameters and segmented configurations in dense sand. Larger diameter piles, S2, exhibit higher soil resistance at each depth compared to smaller diameter piles like S1. This behavior occurs because a larger diameter pile provides more surface area in contact with the surrounding soil, enhancing frictional resistance along its surface.

For stepped piles, P1, P2, and P3, representing 2, 3, and 5 segments respectively, soil resistance tends to decrease as the number of segments increases. This reduction in resistance is likely due to discontinuities between segments, which modify the interaction between the pile and the surrounding soil. The segmentation introduces localized shifts in load distribution at each interface, which can reduce the overall skin friction compared to a straight pile.

In dense sand, pile S2 exhibits significantly higher soil resistance when compared to smaller-diameter pile S1. This is primarily due to the increased frictional contact area, which is more effective in dense sand because of its higher density and interparticle friction. The dense sand exerts a stronger lateral confinement on the pile, resulting in greater resistance as depth increases.

In contrast, in loose sand deposits, the overall soil resistance for all piles, including the step-tapered piles, is lower than in dense sand. Loose sand, with lower density, offers less frictional resistance along the pile surface, regardless of diameter. As a result, the difference in soil resistance between larger and smaller diameter piles is less pronounced in loose sand than in dense sand. For stepped piles, P1, P2, and P3, the trend of decreasing soil resistance with an increasing number of segments is also evident in loose sand. However, the reduction in resistance is more significant in loose sand due to the decreased interlocking between soil particles around the segmented interfaces. The discontinuities introduced by the segmentation disrupt the soil-pile interaction more noticeably in loose sand, leading to a marked reduction in skin friction compared to dense sand.

Additionally, the step-tapered design of segmented piles introduces diameter variations along the pile depth, and has a greater impact on loose sand. Since loose sand has lower confining pressure, each tapered segment experiences a further reduction in frictional resistance, resulting in even lower overall soil resistance with depth. Thus, while both dense and loose sands show decreased resistance with an increase in segmentation, this effect is amplified in loose sand due to its lower density and reduced frictional capacity.

V. Discussions

The deflection of all piles is significantly reduced when the sand is dense in comparison to when the sand is loose. Moreover, the results clearly show that the deflection of tapered and stepped piles is less than that of piles with uniform cross-sections. With an increase in the angle of taper for tapered piles and variable sections for stepped piles, the deflection decreased and the load capacity increased. These findings demonstrate that the lateral load-bearing capacity of piles is influenced by the soil fabric, soil density, and the type of pile.

It has been observed that tapered piles exhibited superior performance in resisting lateral loads and less deflection at the pile head compared to piles of uniform diameter. Piles with a uniform diameter also demonstrated greater load-bearing capacity in the dense sand case than in the loose sand. In the loose sand state, it was observed that the lateral load increased with an increase in taper angle. This increase was found to be negligible when the angle changed from 1.5° to 2°. In the case of relatively dense sand, the lateral load exhibited a notable increase up to a taper angle of 1.5° and subsequently exhibited a slight decrease with an increase in the taper angle. This can be regarded as evidence that the sliding friction is increased as the density of the sand is increased, thereby developing a larger resistance to deflection of the pile. A step-tapered pile was observed to carry a greater lateral load than a straight pile with a lesser displacement. In the loose sand condition, the lateral load increased with an increase in the number of segments. In contrast, in the dense sand state, there was a significant increase in the lateral load up to three segments, followed by a decrease after five segments. This may be attributed to the fact that the cross-sectional variation was of a considerable length, thereby preventing the utilization of the full range of structural features associated with a variation in pile cross-section.

Additionally, the load-deflection graphs indicate the occurrence of zero deflection points for the piles, a phenomenon that is readily apparent in the case of shorter piles. As the lateral load increases, the deflection of the pile also increases, with this phenomenon being particularly evident in shallow layers of soil. In the case of rigid piles, the governing factor in failure is typically the rotation of the pile about the critical position. The implosion of the soil wedge and the pile deflection predominantly occur above this position. Subsequently, the deflection ceases to alter at this point of primary zero displacement, a phenomenon known as the insertion effect. This is due to the necessity for significant displacement to mobilize the passive resistance of the soil at the pile toe.

The deflection of the piles exhibited a linear trend when observed in the loose state, as illustrated in Figures 14 and 15. This trend was observed to be either tapered, step-tapered, or straight. However, in dense sand conditions, there was evidence of flexural deformation, indicating that the pile behaved in an elastic manner rather than as a rigid member, as observed in the loose state. This is attributable to the rise in the ratio of pile-soil stiffness with an increase in relative density. In comparison, the point of zero displacement was observed to occur at a lower level in the dense state of the sand than in the loose state of the sand. Furthermore, the particles in dense sand conditions are packed closely and exhibit reduced mobility compared to a loose sand state.

To ascertain the efficacy of a pile in resisting lateral loads, the ultimate load is expressed as the load/bearing capacity ratio. This is defined as the ratio of the ultimate load of a tapered or step-tapered pile to the ultimate load of a reference pile. As illustrated in Table 4, the tapered pile demonstrated an increase in ultimate load ranging from 15% to 50% in loose sand and 30% to 70% in dense sand conditions. In comparison, pile T4 demonstrated the greatest increase, reaching 68% and 52% in dense and loose conditions, respectively. A similar pattern was observed for the remaining piles, T1, T2, and T3. This is due to the increase in the top cross-sectional area, which offers increased stiffness and, therefore, greater effectiveness of the tapered pile.

TABLE 4
PILE LOAD CAPACITY RATIO

	Case	Pile	Variations				
			S	**T1**	**T2**	**T3**	**T4**
P_u (N)	Loose	Taper	21	24.32	25	30.9	32
	Dense		43	57	61.2	74.5	72.5
			S1	**P1**	**P2**	**P3**	**S2**
	Loose	Step-taper	20.5	28.73	29.09	34.72	25.82
	Dense		42.85	60.62	77.55	52.14	55.64
k_h				**T1**	**T2**	**T3**	**T4**
	Loose	Taper		1.15	1.19	1.47	1.52
	Dense			1.33	1.42	1.73	1.68
				P1	**P2**	**P3**	**S2**
	Loose	Step-taper		1.40	1.42	1.69	1.26
	Dense			1.41	1.80	1.23	1.30

P_u - Ultimate lateral load, k_h – Ratio of capacity

In the case of step-tapered piles, an increase in the lateral load was observed, ranging from 20% in dense to 70% in loose sand. The step-tapered pile with five segments exhibited a 69% higher load-bearing capacity in loose sand compared to other piles. However, the situation differs when the sand is in a dense state, exhibiting a decline in performance. The pile demonstrated an increase in capacity of 23%, a comparatively modest gain when compared to that of P1 and P2, and similarly so when compared to that of S2. This observation indicates that an appropriate variation in the cross-section position has a discernible effect on the load and deflection of stepped piles. It is therefore recommended that the position of the variable cross-section be maintained between 25% and 45% of the length of the pile. In comparison, step-tapered piles demonstrated superior load-bearing capabilities in both loose and dense sand conditions, exceeding the performance of tapered piles. This is due to the variation in surface area being greater for stepped piles and larger pile heads than for tapered piles.

At the surface (0 m depth), the pile experiences the largest deflections due to the reduced confinement of the surrounding soil, resulting in large negative soil reaction values. These negative values indicate significant compressive forces as the soil pushes back strongly against the pile's movement. As the depth increases the soil becomes more confined and provides greater lateral support, which reduces the deflection of the pile. Consequently, the soil reaction values decrease in magnitude, reflecting less compression. At greater depths, around 0.5 m, the deflection becomes negative, meaning the pile is pushing back against the soil, causing the soil reaction to shift to positive values. This indicates tensile forces as the pile encounters more resistance from the surrounding soil and experiences less movement. Overall, this trend is typical in laterally loaded piles, where the soil's resistance increases with depth due to greater confinement and stiffness, leading to reduced deflection and changing soil reaction forces.

In the present study, the sand was deposited around the pile using a raining technique, as distinct from the alternative method of pushing the pile into the soil mass. The installation method employed did not result in the observed densification of the sand that typically occurs during pile driving. Therefore, the results obtained do not reflect the behavior of driven piles. In practical field conditions, however, it is anticipated that these piles will bear a greater load due to the driving effect, specifically the wedge action of tapered piles during driving, than straight piles. Additionally, the driving behavior of step-tapered piles is analogous to that of tapered piles [73]. The effect of stiffening the model tank wall was considered to be minimal for two reasons. Firstly, the pile was placed at a distance greater than four times the diameter of the tank wall. Secondly, at the level of loading where high deformation occurs, it was assumed that the deformation was confined to the vicinity of the pile, and therefore the edge effect was not significant.

VI. SUMMARY AND CONCLUSIONS

Tapered and step-tapered piles offer advantages over uniform-diameter piles in several areas, including load-carrying capacity, material distribution, and the capacity to withstand high loads over shorter driven lengths. The present experimental study comprises a series of twenty horizontal loading tests conducted on model straight, tapered, and step-tapered piles in a relatively large laboratory setup. The objective of this investigation is to examine the response of piles to horizontal loads in sand deposits. The study encompassed the influence of soil density and pile shape attributes on the evolution of pile resistance to lateral loads. Pile head displacement, ultimate load, and pile deflection relationships were derived from the measured strains and response of piles. The following conclusions were drawn from this experimental investigation:

(1) The behavior of a pile subjected to lateral loads is contingent upon the density of the surrounding soil and the geometric characteristics of the pile structure, including the taper angle and the number of segments.

(2) The pile taper exerts a significant impact on the lateral bearing capacity of the pile. The tapered pile, with a taper angle of 2°, which has an identical volume to that of the reference cylindrical pile, demonstrated a lateral resistance that was approximately 68% and 52% larger in dense and loose sand, respectively.

(3) The provision of segments or steps for piles has a notable effect on their bearing capacity. The stepped pile with five segments demonstrated a 69% increase in load capacity relative to the straight pile.

(4) In comparison, the tapered and step-tapered piles exhibited reduced pile head deflections in response to lateral loads relative to uniform-diameter piles. Furthermore, in addition to depth, tapered and step-tapered piles exhibited reduced deflections compared to straight piles.

(5) The response of the tapered and step-tapered piles to lateral loads was superior to that of the straight/uniform diameter pile. However, an optimal angle in the range of 1° to 1.5° was identified for tapered piles, while an optimal segment in the range of 3 to 5 segments was determined for step-tapered piles.

(6) Taper piles reduce bending moments and achieve more uniform stress distribution due to higher stiffness and moment of inertia from taper angles, improving resistance, especially in dense sand.

(7) Stepped piles, particularly with more segments, also enhance bending resistance and stress distribution compared to uniform-diameter piles, offering better performance in both loose and dense sand.

(8) Step-tapered and tapered piles exhibit higher soil resistance in dense sand due to increased frictional interaction, while in loose sand, resistance is reduced, particularly for segmented configurations, as lower confinement and discontinuities between segments weaken the soil-pile interaction.

(9) Furthermore, the behavior of pile T3 was found to be consistent in comparison to piles T1, T2, and T4, regardless of the soil state. Consequently, a taper angle of 1.5° was identified as the optimal angle under all soil conditions.

(10) Similarly, in the case of step-tapered piles, pile P3 demonstrated consistent performance when compared to piles P1, P2, and S. Therefore, irrespective of soil condition, 3 segments were considered optimal.

The present study will facilitate access to foundations for structures such as tall structures, oil platforms, wharves, jetties, and structures in marine habitats, where large lateral loads are anticipated. In general, tapered and step-tapered piles offer greater material savings than uniform cylindrical piles. Furthermore, the use of variable section piles may enhance the performance of pile foundations in resisting lateral loads. However, in terms of practical applicability, tapered piles can be more readily driven due to their wedging mechanism than step-tapered piles, where edge resistance tends to impede the driving process.

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