IJE TRANSACTIONS A: Basics Vol. 36 No. 01, (January 2023) 28-34

International Journal of Engineering

Journal Homepage: www.ije.ir

# Experimental Study of Lateral Loading on Piled Raft Foundations on Sandy Soil

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*PAPER INFO*

*Paper history:*
Received 16 July 2022
Received in revised form 25 September 2022
Accepted 09 October 2022

*Keywords*:
*Pile Raft Foundation*
*Soil-Structure Interaction*
*Settlement*
*Portable Travelling Pluviator*
*Bearing Pressure Enhancement*

*ABSTRACT*

A Shallow foundation on cohesionless soil cannot support greater weights; piled raft foundations are recommended because they combine the load-bearing qualities of piles and raft. Combined Piled Raft Foundations (CRPF) are efficient for tall buildings because they account for both vertical and lateral loads. In a pile raft foundation, the raft's load-resistance is disregarded due to soil-structure interaction. Simplification may lead to an uneconomical design. While study on raft's vertical resistance is extensive, its horizontal resistance is limited. In the present study, 160 mm x 160 mm pile-raft model with different pile spacing and pile length was tested. Studies showed that pile length and spacing of pile improve bearing capacity and reduce settlement of raft. The pile raft system rests 65 percentage of the lateral load, depending on pile spacing and its length. Pile spacing and pile length lessen the raft's lateral load contribution. Furthermore, as increasing in pile spacing reduces raft overturning by 60 percentage. Upgrade pile raft system design may make a cheaper and more efficient option for skyscrapers and make this foundation system more economical design.

***doi**: 10.5829/ije.2023.36.01a.04*

## 1. INTRODUCTION

In circumstances where a raft foundation alone doesn't meet design criteria, adding piles can improve a raft's performance [1]. Piled raft foundations (PRFs) were first proposed by Poulos and Davis [2]. In a later study, Burland et al. [1] suggested employing the pile group to lessen the effects of settlement. Several studies have analyzed the piles' and the raft's load-carrying capacities to develop better design strategies for Piled raft Foundation Systems (PRFs). The PRFs' behavior and load carrying capability can be analyzed using a variety of simplified approaches [3], semi-analytical methods [4], and numerical methods [5]. In typical pile-raft design, the raft's contribution to vertical and lateral load resistance is often overlooked [6]. Recent experiments employing small and large-scale models have examined the raft's vertical load contribution [7]. In the modern context, designers integrate not only vertical load, but also lateral load contribution, which has an impact on soil bearing capacity, pile length, and spacing [8]. The raft in Combined piled raft foundation (CPRF) reduces the cost of tall building foundations. Its lateral load contribution is rarely studied. Very little research has been done on pile rafts under lateral loads like earthquakes, retaining wall pressure, and wind. Laterally loaded piled raft response is governed by pile-head rigidity, relative stiffness, pile spacing, pile-soil, pile-pile, and raft-pile interactions [9]. The complex behavior of piled raft foundations subjected to horizontal loads is poorly understood [10]. A seismic design concept for piled raft foundations is needed in highly seismic places like Kutch, Gujarat (India) [11]. Pile-raft foundations have been used in India; however, most seismic designs ignore piles [12]. Considering the trend toward performance-based design in geotechnical engineering, the behavior of piled raft foundations subjected to horizontal loads must be justified [13]. This study employed centrifuge modeling to analyze piled raft foundations. Centrifuge modeling helps analyze pile-raft interactions in sandy soils [14]. This paper presents the results of horizontal loading testing on piled raft models and rafts alone. To keep structures from settling, the primary goal of piles in a piled raft is to reduce settlement and avoid overturning

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Please cite this article as: A. Chandiwala, S. Vasanwala, Experimental Study of Lateral Loading on Piled Raft Foundation on Sandy Soil, ***International Journal of Engineering, Transactions A: Basics***, Vol. 36, No. 01, (2023), 28-34

the raft [15, 16]. This study explores the influence of pile length and pile spacing of a pile raft model on loose sandy soil. Underneath this piled raft, nine settlement-reducing piles were tested. Pile-supported raft foundations should be examined for settlement and bearing capacity (such as pile length, and pile spacing). Pile-raft foundations affect performance.

## 2. PILED RAFT FOUNDATION

Design engineers should understand how loads are carried from the raft to piles and soil media so they can predict raft performance like settlement, bearing pressure enhancement, and borrowing capacity rate, as well as pile behavior like displacement and load sharing across piles [17-19]. Pile skin friction in a piled raft foundation helps carry the superstructure's weight. In Figure 1, the raft carries the remaining weight via soil contact. $Q_P$ is the pile weight, $Q_R$ is the raft weight, and Q is the applied horizontal load on a piled raft foundation. The pile-soil-pile interaction is caused by pile spacing and installation style, like free-standing piles [20].

## 3. TEST SETUP

### 3. 1. Soil Properties

Narmada river dry sand has been used for this research work. The sandy soil's physical properties were tested using Indian standards (IS). Table 1 shows the characteristic of soil. Table 2 represents the geotechnical properties of soil. Figure 2 shows the sand gradation curve.

### 3. 2. Model Piled Raft and Tank

The steel tank measured 1000 mm long, in height and width. Each side includes two 2.5-meter-tall columns and two 1.5-meter-tall horizontal beams. Figure 3 shows a schematic view of the model test setup. A mild steel square model raft was made to imitate a narrow structure with horizontal loads. 160 × 160 mm and 10 mm thick, the model raft. The model raft contains holes for vertically-spaced pilings. Each piling was supplied with a 6-mm-diameter, 20-mm-long bolt. Model rafts and piles have 1.8 x $10^5$ MPa elasticity. The piles were 10, 15, and 20 cm long with slenderness ratios of 10, 15, and 20. Model-piled rafts prevent anxiety at the tank's edge. To avoid stiff tank foundations from affecting pile behavior. The model raft's settling was measured by Linear Variable Differential Transformer (LVDT).

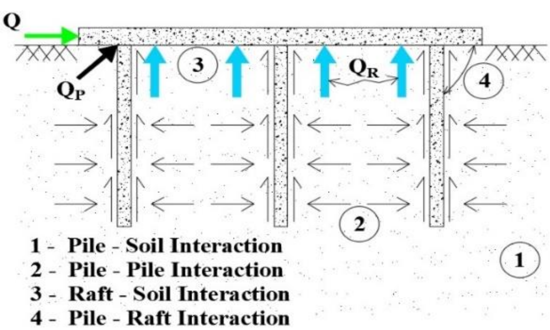



**Figure 1.** Schematic diagram of piled raft interactions

**TABLE 1.** Soil characteristics

| $D_{10}$ | $D_{30}$ | $D_{60}$ | $G_S$ | $\gamma_{min}$ (kN/m³) | $\gamma_{max}$ (kN/m³) | Ø |
|---|---|---|---|---|---|---|
| 0.2 | 0.5 | 0.7 | 2.63 | 14.80 | 17.65 | 37° |

**TABLE 2.** Geotechnical Properties of Soil

| Geotechnical Properties | Values | Units |
|---|---|---|
| Specific Gravity (G) | 2.63 | - |
| Maximum dry density | 17.65 | kN/m³ |
| Minimum dry density | 14.80 | kN/m³ |
| Relative Density at 20% | 15.49 | kN/m³ |

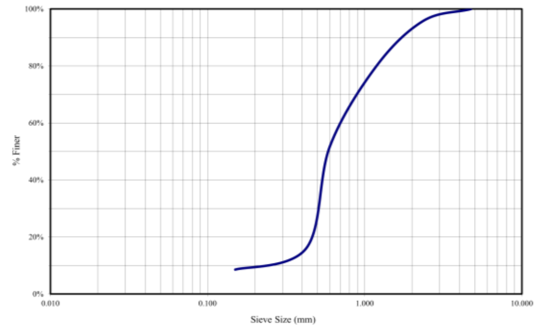



**Figure 2.** Particle size distribution curve for sand

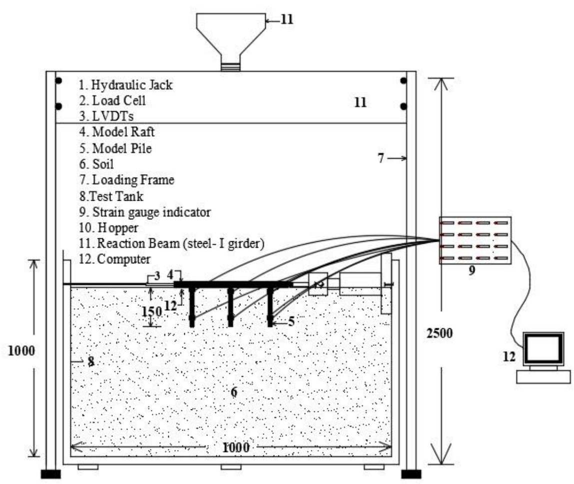



**Figure 3.** Schematic view of the model test setup

As shown in Figure 4, the diffuser sieves were angled to reduce sand flow. Vertically pluviating the tube increased sand dispersion. The sand was redirected using sieves. Thin horizontal layers of sand were pluviated using a stiff vertical tube. Regulating flow generated a steady, uniform sand rain. Flow management prevented sand from collecting on diffuser sheets, ensuring consistent sand rain.

**3. 3. Test Procedure** The portable traveling pluviator (PTP) [21] has a 20-kilogram fixed hopper and a 100-centimeter rigid tube for uniform, reproducible packing. Several model experiments were done to study a horizontally loaded raft on the sand. Figure 5 shows different piles' designs. Installation of non-displacement piles is as follows. First, a Portable Traveling pluviator (PTP) [22, 23] deposited sand, then non-displacement piles needed 28 cm of sand from the tank's bottom. To ensure adequate seating, 20 cm piles with 10 mm penetration were set vertically in the sand. The mounds will remain as long as the tank isn't complete. The model raft was then nutted to each pile. The failure occurred at 0.1 kN/min. LVDT measured raft displacement. Deposition strength, fall height, sand rain uniformity, and particle characteristics determine air pluviation's relative density (Rd) [24]. Structural piles were instrumented with 350 Ω strain gauges at their uppermost portion, below the raft's level. The load in the piles at the strain gauge's plane is calculated from the recorded strain and predicted using the equation:

$$Q = \varepsilon \, x \, A_p \, x \, E_p \tag{1}$$

where Q is load (kN), ε denotes the measured strain (microstrain), $A_p$ indicates the c/s Area of the pile ($m^2$), and $E_p$ is the Modulus of elasticity of pile ($kN/m^2$).

Twenty-channel strain gauges were used to measure pile stresses. The locally-made strain indicator provides precise, high-resolution strain measurements. The tape protected and sealed the strain gauge. Mild steel rafts and piles had elasticity moduli of 1.8 x $10^5$ MPa and 0.2, respectively. Table 3 shows the experimental program of the raft and piled raft to study pile length (L), spacing (P), and pattern. Figure 6 illustrates three piled raft models with different piling designs. The pattern I had nine 10

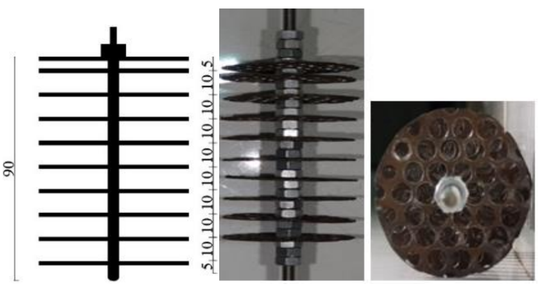
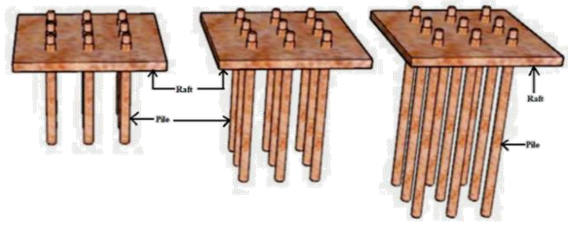


**Figure 4.** Experimental diffuser arrangement

cm piles, Pattern II had nine 15 cm piles, and Pattern III had nine 20 cm piles (Pattern III). All trials used nine piles. Figure 7 shows the pile spacing employed in the study: 3d (Arrangement 1), 4d (Arrangement 2), and 5d (Arrangement 3) for a 160 mm x 160 mm piled-raft system. Repeatability and consistency were tested. Load-settlement patterns differed by only 2.5% in maximum

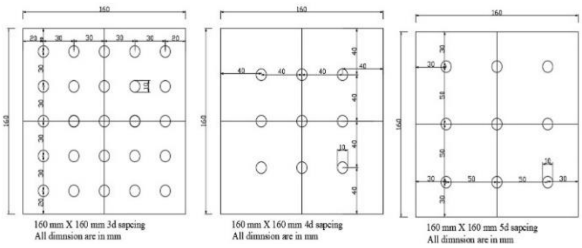



Pattern I Pattern II Pattern III

**Figure 5.** Pile arrangement configuration of 160 mm x 160 mm piled raft

**TABLE 3.** Experimental Test Programme

| Series | Constant Parameters | Spacing of piles | No. of Piles |
|---|---|---|---|
| 1 | Unpiled Raft | | |
| 3 | Piled raft; L/d = 10 | 3d,4d,5d | 9 |
| 4 | Piled raft; L/d = 15 | 3d,4d,5d | 9 |
| 5 | Piled raft; L/d = 20 | 3d,4d,5d | 9 |



Arrangement 1 Arrangement 2 Arrangement 3

**Figure 6.** Various pile spacing for 160 mm x 160 mm piled raft

**Figure 7.** Horizontal load applied on model piled raft foundation

settlement values. The difference was ignored. Figure 7 shows the horizontal load applied on the model pile raft foundation. The following steps were part of the test methodology: Sand was placed using the Portable Traveling Pluviator (PTP) rainfall method [25]. The tank's bottom required to be 28 cm above the non-displacement piles in height. 20 cm long piles with a 10 mm penetration were placed vertically in the sand to ensure proper sitting. The heaps will stay put so long as the tank isn't finished. The model raft was then screwed onto each pile following that. A loading platform was used to load the model raft. The load was applied at 0.1 kN/min till failure. The maximum load capacity of a raft is frequently calculated as the settlement equal to 10% of the width [26-28]. The raft was loaded as a result until it settled at least 10% of B, or 16 mm.

## 4. RESULTS AND DISCUSSION

Over 20 model tests on prototype rafts for cohesionless soil are shown. The horizontal load behavior of rafts supported by varied pile arrangement patterns was studied. The influence of $A_{GPR}$ on raft settlement, bearing pressure enhancement, and raft tilt are examined.

**4. 1. Influence of Pile Length** The settlement was measured for 0.1 pecent of width of raft. Figure 8 shows typical changes in ultimate load versus raft center settling at 16 mm settlement for different L/d ratio. Raft horizontal load, Figure 8 shows that rigid piles increase load-carrying capacity with less settlement.

The graph indicates that a rigid pile affects a raft's load-carrying capacity when horizontally loaded. Pile length boosts a raft's load-carrying capacity. Figure 9 shows that the unpiled raft's load-carrying capability (2.03 kN) increased to 3.94, 4.47, and 4.98 kN for

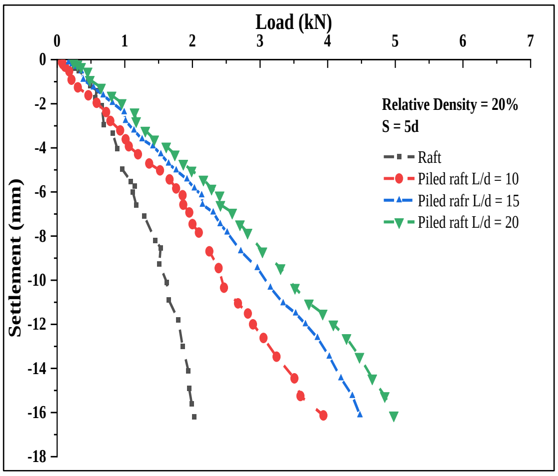



**Figure 8.** The behavior of raft and piled raft for various pile length

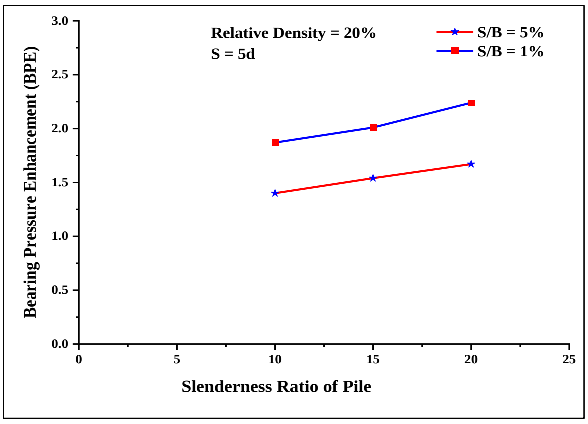



**Figure 9.** Effect of L/d ratio on BPE with respect to various S/B ratio

L/d = 10, 15, and 20, respectively. As the pile length increases, skin friction increases, boosting the raft's load-carrying capability.

Figure 9 shows how the S/B ratio (1 percent and 5 percent) affects raft bearing pressure with different L/d ratios. L/d ratios for both S/B ratios boost the raft's maximum load-bearing capability. As pile length rises, rigidity reduces [12]. Long piles may be better than short ones for reducing horizontal raft settling. However, increasing pile length improves the stiffness of the piling raft system.

**4. 2. Impact of Pile to Raft Area Ratio** The influence of pile arrangement on model raft footing performance on loose sand under horizontal loads was tested using three pile slenderness ratios. As in Figure 6, Figure 10 shows the model raft's load settlement behavior. The 5d spacing configuration offers a more significant area proportion of the pile to the raft. As a result, it indicates higher stiffness and load-carrying capacity than the 3d and 4d spacing configurations for

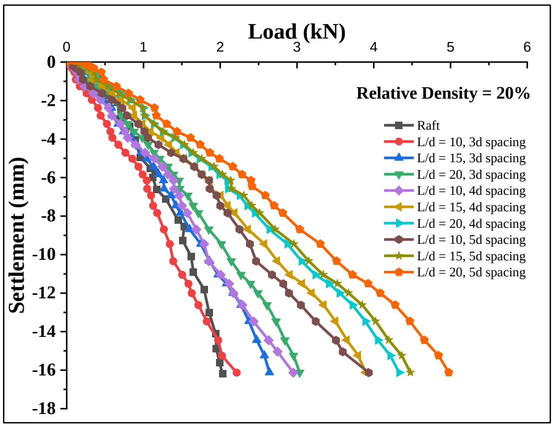



**Figure 10.** Ultimate load variation with maximum settlement for various $A_{GPR}$

horizontal loading. This is because the 5d spacing configuration gives a more significant area proportion of the pile to the raft. Nine 5d-spaced piles are stiffer and resist tilting better. This model illustrates minimum differential settlement due to a larger pile-to-raft ratio. 3d and 4d pile arrangement patterns concentrate more in the raft's center, reducing rigidity. Other researchers [13] have noted that piles are concentrated in the plate's center, and that settlement is lower in the middle but higher on the outside.

**4. 3. Influence of Model Raft's Tilt** Figure 11 illustrated the settlements along the center line portions of the model rafts when they were loaded with horizontal load applied along the width of the raft and kept on loose sand to evaluate the effect that different pile design had on the behavior of the rafts. In Solitary, piles tied to a raft with L/d=20 and raft settlements are plotted. At the same minimum load level (the unpiled raft failure load illustrated in Figure 8), the settlement values for each of the various pile design were calculated and compared to one another [14]. The graph indicates that using a pile layout with a 5d spacing will result in a reduction in the maximum raft settlements and tilt. The maximum settlements decreased from 16.18 millimeters to 10.75 millimeters, 6.68 millimeters, and 2.44 millimeters, respectively, when 3d, 4d, and 5d pile layouts were adopted. In the 5d pile configuration, the $A_{GPR}$ is increased, and as a consequence of this, the horizontal load resistivity is enhanced. As a result of this, the tilt is decreased in comparison to the 3d and 4d arrangements.

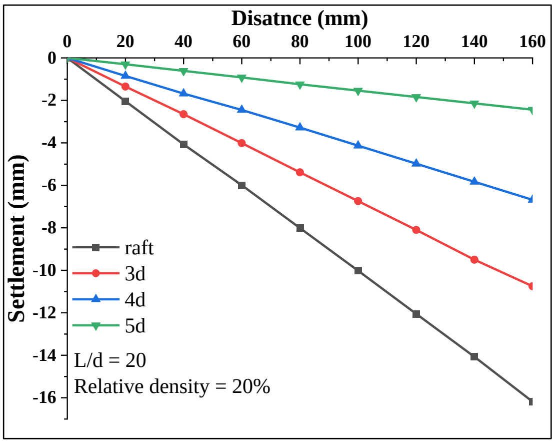



**Figure 11.** Tilt of raft and piled rafts for different pile spacing

## 5. CONCLUSION

The effectiveness of using short vertical piles under a raft with a secure attachment was investigated. A number of different piles spacing and pile length configurations in loose, cohesionless soils were investigated. Previous settlement research reveals numerous elements that affect the settlement of pile-supported rafts. Under the same loading and soil conditions, the length and spacing of piles reduce total settlement and increase their load-carrying capacity. The following is a list of the most important things that were learned from the laboratory experiments:

- It has been found that when a raft is subjected to a horizontal load for settlement of 0.1% of the raft's width, the load-carrying capacity of the raft is enhanced. When compared to raft foundations, piled rafts with L/d ratios of 10, 15, and 20 have an improved load carrying capability of 48.33 percent, 54.65 percent, and 59.29 percent, respectively. As the pile length increases, skin friction causes an increase in carrying capacity for the pile.
- When the S/B ratio is 1 percent and 5 percent, as well as when the L/d ratio is 10, 15, and 20, it is noted that the performance to resist bearing pressure has improved. The bearing pressure is increased for all L/d and S/B ratios. The S/B ratio of 1 percent results in a maximum increase in bearing pressure of 14.15 percent, whereas the S/B ratio of 5 percent results in 19.78 percent. The longer pile's increased ultimate load-bearing capacity allows it to withstand greater bearing pressure.
- Load-bearing capability of piled raft foundations can be increased significantly by varying pile spacing and the L/d ratio. Out of 3d, 4d, and 5d spacing arrangements for different L/d ratios, the 5d arrangement performs better than the other arrangements under horizontal loading. With respect to the raft, the maximum increase in ultimate load-bearing capacity is 49.26%, 52.23%, and 63.29% for 3d, 4d, and 5d spacing, respectively. Increases in pile spacing result in a larger pile group's center core area (CCA). As a result, at 5d spacing, the horizontal load carrying capability rises. Having a larger pile to raft area ratio means that the pile group's Contribution to the raft's overall rigidity is greater than the raft's center section alone. According to a study, the 5d arrangement of piles is also more resistant to an overturning moment when situated near the edge.
- The tilt of the raft dramatically decreases as the pile spacing increases from 3d to 5d. The tilt of the raft is reduced to 2.44 millimetres for 5d spacing, from 16.18 millimetres for raft only. Tilt edges for a horizontal load diminish as pile spacing increases because a bigger area of the piled raft contributes to the resistance of the overturning moment.

The present study demonstrates that pile length plays a crucial role in preventing raft foundation settlement. However, pile spacing plays a crucial contribution in increasing the bearing capacity of the foundation and reduce the overturning as a whole. This study focuses exclusively on soft soil. However, this type of study can also be conducted by modifying the soil type and soil conditions.

## 6. ACKNOWLEDGEMENT

The authors would like to express their gratitude to the Department of Civil Engineering at the Sardar Vallabhbhai National Institute of Technology in Surat, India, for all of the help that was provided in many forms to make this research possible.

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## Persian Abstract

**چکیده**

یک پی کم عمق روی خاک بدون چسبندگی نمی تواند وزنه های بیشتری را تحمل کند. پایه های شمع قایق توصیه می شود زیرا آنها ویژگی های باربری شمع و قایق را با هم ترکیب می کنند. پایه های شمعی ترکیبی (CRPF)برای ساختمان های بلند کارآمد هستند زیرا هم بارهای عمودی و هم بارهای جانبی را شامل می شوند. در فونداسیون رافت شمعی، به دلیل برهمکنش خاک و سازه، مقاومت در برابر بار رافت نادیده گرفته می شود. ساده‌سازی ممکن است منجر به طراحی غیراقتصادی شود. در حالی که مطالعه روی مقاومت عمودی قایق گسترده است، مقاومت افقی آن محدود است. در مطالعه حاضر مدل شمع-کلک ۱۶۰ میلی متر در ۱۶۰ میلی متر با فاصله شمع ها و طول شمع های مختلف مورد آزمایش قرار گرفت. مطالعات نشان داد که طول شمع و فاصله شمع باعث بهبود ظرفیت باربری و کاهش نشست قایق می شود. بسته به فاصله شمع ها و طول آن، سیستم قایق شمع ٦۵ درصد از بار جانبی را تحمل می کند. فاصله شمع ها و طول شمع سهم بار جانبی قایق را کاهش می دهد. علاوه بر این، با افزایش فاصله شمع ها، واژگونی قایق تا ٦۰ درصد کاهش می یابد. ارتقاء طراحی سیستم رافت شمع ممکن است گزینه ارزان‌تر و کارآمدتری برای آسمان‌خراش‌ها باشد و این سیستم پایه را طراحی اقتصادی‌تر کند.