Journal of Science and Technology in Civil Engineering, HUCE, 2023, 17 (2): 62–69

DEVELOPMENT OF NEW ROTATION PILE TECHNOLOGY MIRAI PILE® AND PRELIMINARY STUDY IN VIETNAM ON CONSTRUCTION

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Article history:
Received 23/12/2022, Revised 10/5/2023, Accepted 12/5/2023

Abstract

In recent years sustainability and environmental impacts have been highlighted as an important issue in design and construction particularly in urban area in construction of buildings and bridges. Mirai pile® (M-pile) is new rotating pile technology, which was developed in 2020, is highly appreciated for its environmentally friendly functions such as: rapid construction, low noise; low vibration; no waste soil during construction; no ground water contamination. In this study, construction sequence and prediction of axial bearing capacity of M-pile on cohesive soil were introduced. M-pile analysis used with outer diameter of 318.5 mm and thickness of 12.7 mm. The analysis results show that the ultimate bearing capacity prediction of M-pilein soft clay soil considerably increase compared with bored and cast-in-place piles with the same diameter and depth thanks to multiple blades welded along the pile shaft.

Keywords: Mirai pile; new rotation pile technology; rotary penetration; friction bearing capacity; installation torque; cohesive soils.

https://doi.org/10.31814/stce.huce2023-17(2)-06

1. Introduction

In recent years, the rapid urbanization and industrialization are progressing in many developing countries. The construction of core infrastructures such as urban transportation, subways around big cities, power plants, airports, and harbors are progressing rapidly. In urban areas, in order to carry out such development, sustainable and environmentally friendly design and construction that can align with difficult construction conditions in urban cities, such as limited time and space, are required. Accordingly, with the continuous development of pile foundations, various special-shaped piles have emerged to meet the requirements mentioned above [1]. Recently, there has been increasing interested in the rotary steel pipe pile construction method, which can be constructed in narrow areas to ensure a rapid, low noise, low vibration, and does not require earth removal [2–5]. New rotary penetration

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steel pile (hereinafter referred to as the Mirai pile or M-pile) was invented by Marina kawai JFE steel corporation, for soft soil, in which the piles are lowered into the intermediate layer instead of penetrated into the deeper layer. As a result, the bearing capacity of the pile is significantly improved without the need to lower the pile too deeply into soil below.

The geology condition in Hanoi city normally includes a thick layer underneath the soil covering layer which has weak bearing capacity [6]. Therefore, pile foundation is normally designed with its toe placed in the much deeper layer with strong bearing capacity (e.g., 50- to 60-m depth). In order to address this issue and make shorten construction time and easier, M-pile method was studied and developed. Similar screw piles [4, 7–9] and helical piles [10–15], the great advantage of this method is that pile can stop in the soft layers while still being able to provide a high resistance bearing capacity (i.e., end-bearing resistance or shaft resistance) and suitable for many soil types such as sand, fill, and clays. Therefore, the pile's length is not necessary to penetrate the hard soil layer to increase the load capacity, but still can achieve the load capacity according to the design requirements. Unlike as screw piles that the bearing capacity of piles increases mainly due to screw teeth along the shaft, M-pile technology can provide a large bearing capacity and uplift resistance capacity due to the expansion of toe wing. Lately, a few experimental and field studies on steel rotation pile (SRP) was performed by researchers [2, 16, 17]. Saeki and Ohki (2000) [9] conducted full size pile installation and loading tests of screw steel pipe pile. Their results revealed that the characteristics of pile penetration are strongly influenced by spiral wing diameter, angle and shape. Kuzu et al. (2020) [17] presented the results of the field vertical loading test of SRP in Vietnam. Otake et al. (2021) [5] proposed a new method to estimate the side friction of rotary penetration steel pipe pile (RPS-pile) based on the real-time information on the pile-head torque and the auger penetration depth per revolution obtained during piling. However, very few attempts have been conducted to investigate the ultimate capacity of steel pipe pile with multi-stage wings on the skin so far.

Based on the aforementioned discussion, the main objective of the present study is to (1) introduce a new rotating pile technology (known as M-pile) for construction of the deep foundations; (2) analyse and estimate the ultimate push-in bearing capacity of M-Pile. The results of this study would provide valuable information on the effectiveness of M-pile technology applied to infrastructure projects in urban areas in Vietnam in the future.

2. Features of M-pile

2.1. M-Pile structure

M-pile is a friction-reinforced steel pipe pile with multi-stage wings that penetrate into the ground with a rotational motion powered by an electric motor or a hydraulic motor. The bottom wing at the edge and wings on the skin of the steel pipe pile consist of a pair of half doughnut-shaped steel sheets. On the skin of the steel pipe pile, multiple wings in identical shapes are attached at regular intervals. The typical structure of a M-pile is shown in Fig. 1. The ratio of the diameter of bottom wing to diameter of the steel pipe ranges from 1.5 to 2.5 to provide powerful penetration into the ground. Table 1 displays the most standard dimensions of the M-Pile, as well as their scope of application.

2.2. M-pile installation torque

M-piles are installed by applying torque to the pile head, which enables the skin wings and bottom wing to "grab" and advance the pile into the soil. The applied torque, in most instances, is provided via a driving head (hydraulically powered rotary motor). The required torque varies depending on the pile specifications, soil property, or wings diameter. However, the pile material may become damaged if the limit torque specified for each pile material and dimension is exceeded. Fig. 3 presents the relationship between the pile diameters used in construction and the required torque as a guideline based on construction records.

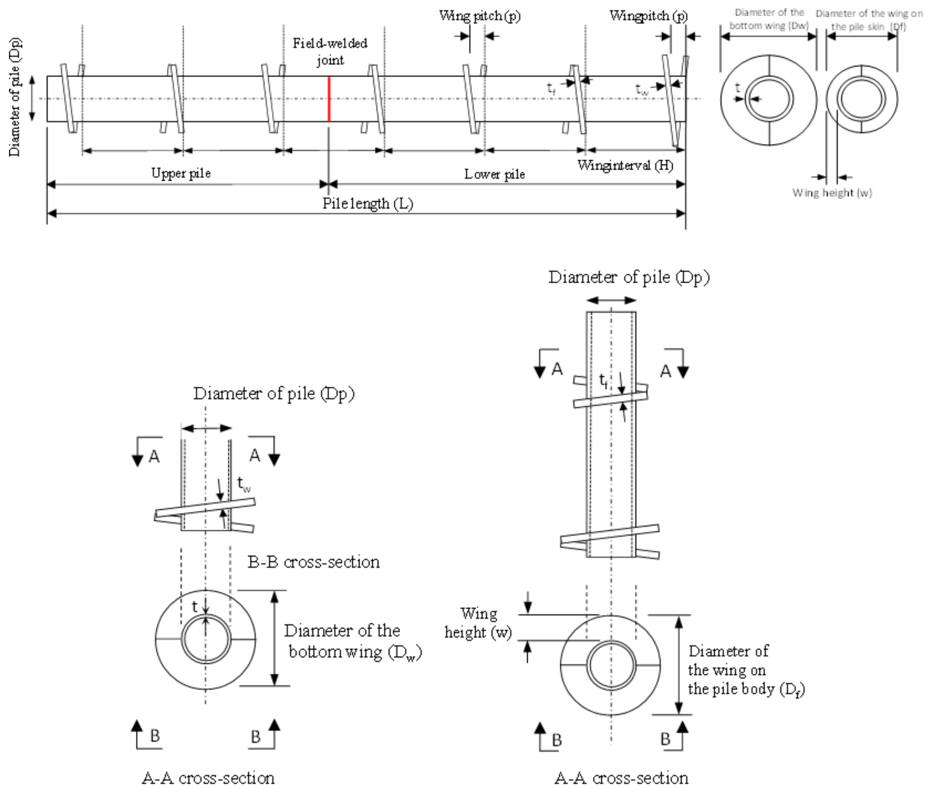

Figure 1. The configurations of Mirai pile®

Table 1. The scope of application of M-Pile

Parameter	Value
Pile diameter, D_p	ϕ114.3 to ϕ800 mm
Wing diameter, D_w	Bottom wing: $D_w = D_p \times 1.5$ to 2.5 Skin wing: $D_f = D_p \times 1.5$ to 2.0
Maximum penetration depth	60 m
Supporting layer	Sand, gravel, and cohesive soils ($N < 50$)

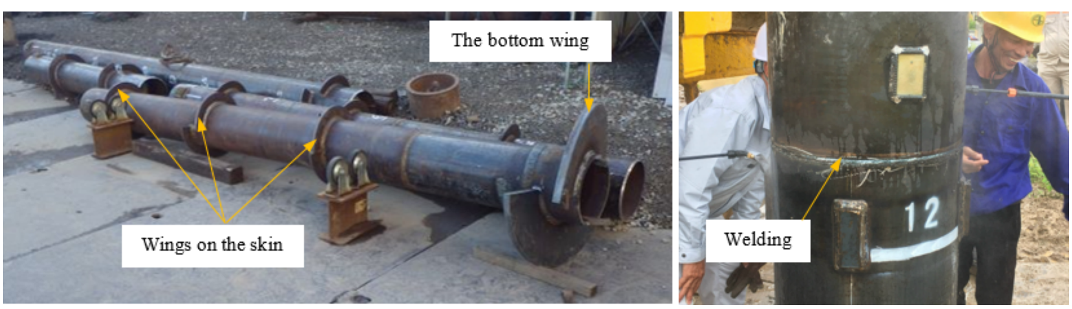

Figure 2. Photographs of M-pile

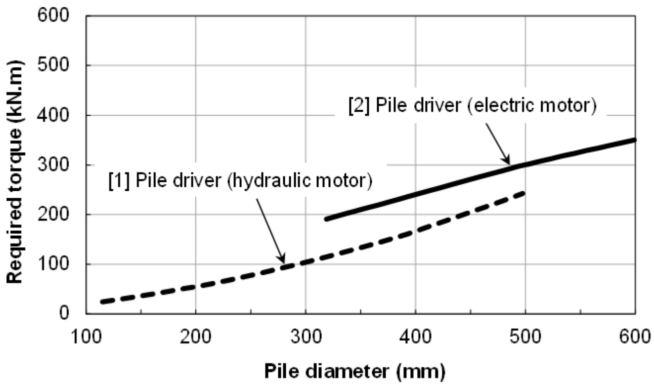

Figure 3. The relationship between pile diameter and required torque by motor using an electric motor or a hydraulic motor

2.3. Construction method

Generally, the construction machines (i.e., small piling machine) for M-pile installation depending on pile diameter and required rotating torque. Fig. 4 shows the profile sketch of a pile head rotation type rotary penetration machine.

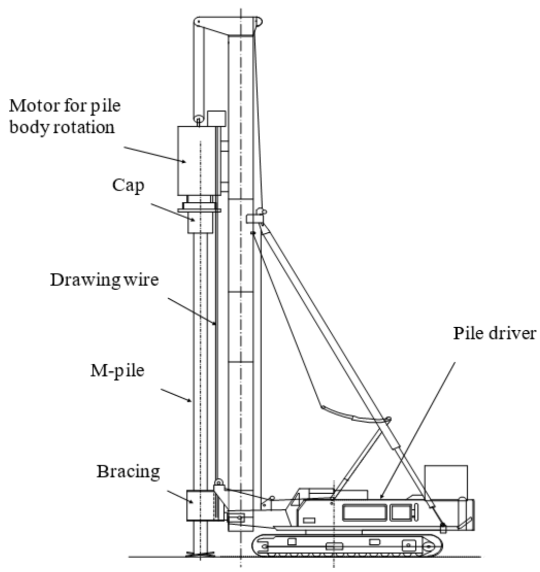

Figure 4. Profile sketch of pile head rotation type rotary penetration machine

3. Theoretical concept for calculating vertical compression bearing capacity of M-pile

The prediction of the axial capacity of rotation piles still poses many challenges for geotechnical and geologists engineering. Some design guidelines [18, 19] only provide bearing capacity formula for steel rotation pile with a helical blade welded to the tip. Based on the specifications for highway bridges Part IV (JRA 2012) [20], a major design standard in Japan, the ultimate push-in bearing capacity of M-Pile (also called axial compressive load capacity) can be determined using the following equation

$$R_u = u_f \sum L_{fi} f_{fi} + u_p \sum L_{pi} f_{pi} + q_d A_w \tag{1}$$

where R_u is the ultimate bearing capacity of the pile; D_f is outer diameter of peripheral wing (m); D_w is tip wing diameter (m); $u_f = \pi D_f$ is perimeter of the part with the peripheral wing (m); $u_p = \pi D_p$ is perimeter of the part without peripheral wings (m); L_{fi} is thickness of layer with peripheral wings (m); L_{pi} is thickness of layer without peripheral wings (m); $A_w = \frac{\pi}{4}\left(D_w^2 - D_p^2\right)$ is the effective area of the tip wing (m^2); q_d is the ultimate bearing capacity per unit area at the pile tip, $q_d = 125N\ (\leq 3750)$ (kN/m^2) (hereinafter, tip resistance); f_{fi} and f_{pi} are unit friction force the layer with and without the peripheral wings, respectively (kN/m^2) (hereinafter, side resistance). The tip resistance (q_d) and the side resistance (f_{fi}, f_{pi}) vary depending on soil type. Table 2 provides the unit friction force values f_{fi} and f_{pi} for different soils.

Table 2. Recommended value of unit friction force for various soil types

Soil type	f_{fi} (kN/m^2)	f_{pi} (kN/m^2)
Sandy soil	4 N (≤ 120)	2 N
Cohesive soil	8 N or c (≤ 120)	8 N or c (≤ 120)

Note: c is the soil cohesion (kN/m^2) = $q_u/2$ with q_u is the uniaxial compressive strength; N is number of blows from the Standard Penetration Test (SPT).

In case of hard soil supporting layer when the maximum N value is larger than 30, the ultimate bearing capacity at the end of pile, q_d (kN/m^2) is recommend as follows

Table 3. Ultimate unit bearing capacity at pile tip according to D_w/D_p and the type of soil

Soil type	D_w/D_p	q_d (kN/m^2)
Sand layer	1.5	120 N (≤ 6000)
	2.0	100 N (≤ 5000)
Gravel layer	1.5	130 N (≤ 6500)
	2.0	115 N (≤ 5750)

Note: N is the SPT value at the end layer. However, the maximum N value is 50.

For shaft resistance, the maximum unit shaft force for each layer of embedded soil can be determined as shown in Table 4.

Table 4. Maximum unit shaft force

Ground type	f_{fi} (kN/m^2)
Sandy soil	3 N (≤ 150)
Cohesive soil	c or 10 N (≤ 100)

N is SPT value on peripheral surface of pile.

4. Pile capacity calculation example

4.1. Geology condition

In this study, the M-pile will be calculated according to the geology of Ha Nam area. Fig. 5 presents the subsurface soil investigation result. The soil profiles are composed as described below: (1) from 0.00 to 1.60 m below ground surface is sand backfill layer, including sand, organic; (2) from 1.60 m to 7.50 m is sandy clay brownish grey, mixed organic, very soft. The N-SPT value ranges from 1 to 2; (3) from 7.50 m to 12.60 m is sandy, brown grey, mixed sand, very soft. The N-SPT value varies from 0 to 2; (4) from 12.60 m to 16.00 m is sandy mixed seashell, blackish grey, brownish grey, loose with N-value of 4 to 8; (5) from 16.00 m to 19.50 m is sandy clay layer, brownish grey, soft to firm with N-value of 4 to 5; (6) from 19.50 m to 21.20 m is sandy clay layer, mixed seashell, darkish grey, firm; and finally (7) from 21.20 m to 25.00 m is sand layer, darkish grey, mixed seashell, medium dense. Fig. 5 also plots the variation of SPT-N with depth and the thickness of each soil layer for borehole HK1. As shown in Fig. 5, the SPT values from 2 m to 12 m below ground surface is quite small with N-value of 1 to 2 blow, indicating a soft soil state.

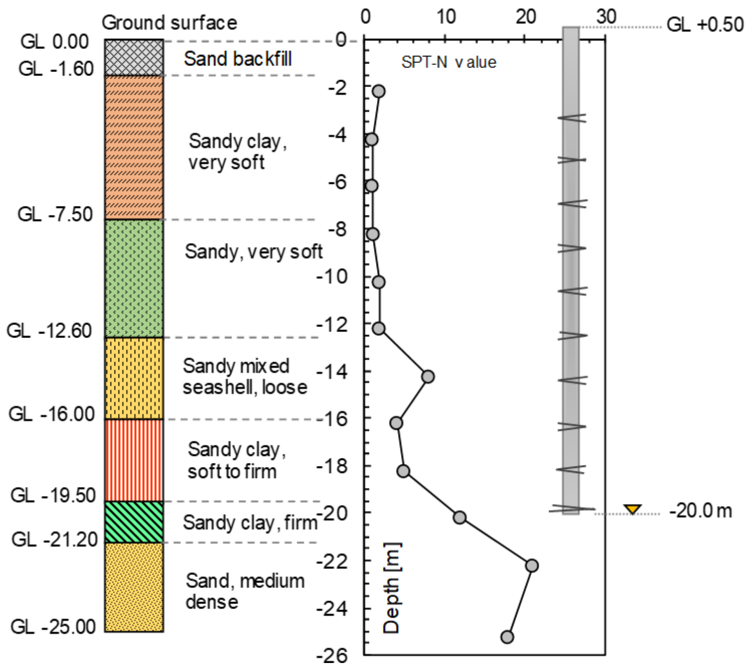

Figure 5. Profile of M-pile and subsurface soil layers

4.2. *M-pile parameter*

M-pile configuration have an outer diameter of 318.5 mm, thickness of 12.7 mm, and the pile length is 20.5 m. The diameter of bottom wing was approximately 2.5 times the pile diameter. Table 5 summaries the pile properties used in this study. A schematic drawing of the M-pile configuration is displayed in Fig. 6.

Table 5. M-pile properties

Parameter	Symbol	Value
Pile diameter, mm	D_p	318.5
Thickness of pile, mm	t_p	12.7
Bottom wing diameter, mm	D_w	796.25
Thickness of bottom wing, mm	t_w	35
Skin wing diameter, mm	D_f	637
Thickness of skin wing, mm	t_f	19

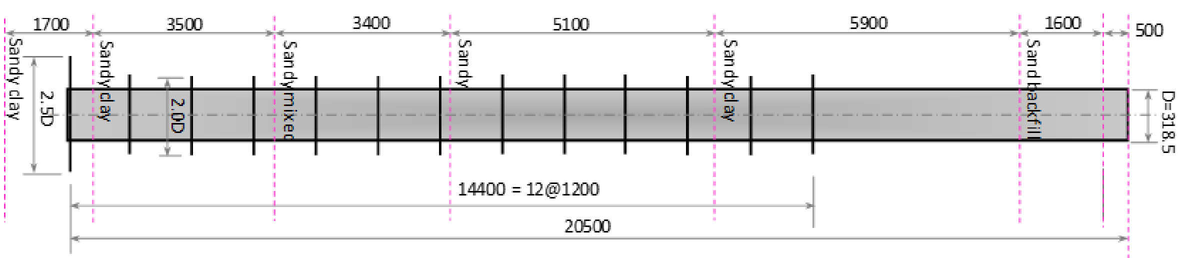

Figure 6. A schematic drawing of the M-pile configuration with D = 318.5mm

4.3. Result and Discussions

The comparison between ultimate bearing capacity of M-pile and other piles are presented in Table 6. It can be observed from Table 6 that the estimated ultimate load value for M-pile, which calculated according to the JRA formula is much higher than of the PHC pile with the same diameter. Only precast concrete pile (i.e., PHC D500 and precast concrete pile 50×50) can provide the same load-carrying value as the M-pile. The ultimate load capacity of M-pile is 200% higher than that of precast concrete pile of 30 × 30 cm. Compared with the all-piles analysed, the M-pile shows a substantial increase in side resistance capacity due to the extension of the wing along the pile body. This is especially effective when most of the body length penetrates the soft soil layers.

The analysis results also indicated that when the soil layer under the pile tip having medium load capacity, the enlarged pile diameter can provide great efficiency in improving the ultimate pile bearing capacity. This is consistent with the conclusions provided by [2, 16, 17] for steel rotation pile and Tsubasa^{TM} pile.

Table 6. Summary of axial pile capacity prediction for different pile types

Pile type	Base resistance (kN)	Shaft resistance (kN)	Ultimate bearing capacity, R_u (kN)
M-pile	**627**	**663**	**1290**
PHC (D300)	233	322	555
PHC (D350)	317	387	705
PHC (D400)	415	453	867
PHC (D450)	525	511	1036
PHC (D500)	648	568	1216
Concrete pile 25×25	206	256	462
Concrete pile 30×30	297	322	619
Concrete pile 40×40	528	453	981
Concrete pile 50×50	825	568	1393

Note: Pile capacity of precast concrete piles was estimated based on Vietnamese standards (Pile Foundation – Design Standard: TCVN 10304:2014).

5. Conclusions

In this study, a summary of new rotating pile technology namely M-pile was presented. The conclusions can be drawn from the results of this study as follows:

- The use of M-piles to support the foundation of structures in urban areas is a viable alternative to conventional methods that offers many advantages including ease of installation, low noise, low vibration, and clean construction environment.

- The analysis results show that the ultimate push-in bearing capacity of M-pile on the basis of N-values is significantly 31%-230% larger than the pile capacity of common prestressed and prefabricated concrete pile with diameter less than 400 mm.

The scope of this study only focused on the prediction of the axial capacity of M-piles. During installation, the expected maximum installation torque, as well as the relationship between the end bearing capacity and installation torque are recommended to be studied. Moreover, the difference configuration of M-pile for each soil type still (i.e., distance between wings, ratio D_w/D_p, D_f/D_p) needs to be continued on field experiment to provide the good performance. Further studies are needed to assess the effect of soil disturbance around the pile when the pile is penetrated on push-in bearing capacity of M-pile. The ultimate compressive capacity of piles based on theoretical should be compared with the results of the in-situ static pile load test to provide a better insight into the load transfer mechanism of M-pile in the future.

Acknowledgements

This study was funded by JFE Steel Corporation, Chiyoda Geotech Co.Ltd, and Hanoi University of Civil Engineering (HUCE) under grant number RD18-21. The financial supports are gratefully acknowledged.

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