

Increasing the carrying capacity of reinforced concrete driven piles by choosing an appropriate cross section

Alaa M. Darwish*, Wameedh G. Abdul-Hussein and Karim H. Al-Helo

Building and Construction Engineering Department, University of Technology, Baghdad, Iraq.

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ABSTRACT

The ultimate carrying capacity of a reinforced concrete driven pile is mainly obtained by calculating the product of its surface area multiplied by the adhesion stress between its shaft and the surrounding soil. For a certain type of soil its average frictional stress with concrete surfaces is taken equal to its value at mid depth of the pile. The surface area of a pile is the product of its cross sectional circumference multiplied by its length. Through this study, it was shown that the circumference of a circular cross section is less by 13% compared to the circumference of an equivalent area square section. A suggested star cross section has been investigated; it was shown that it has an increase of 25% in its circumference compared to a square cross section having a similar area. By adapting the suggested star shape cross section driven pile, it is believed that its carrying capacity will be more than that of a square cross section pile by 25%. In other words, to develop the same required carrying capacity of a group of piles; the suggested star shape cross section driven piles can be driven to four fifths of the required depth of the current similar area square cross sectional piles.

Keywords: Driven pile geometry, driven pile cross section, driven pile depth, star cross section pile.

*Corresponding author. E-mail: darwishmahdy2013@gmail.com.

INTRODUCTION

The purpose of any foundation is to transmit loads to the ground without excessive settlement and shear failure. A piled foundation is used mainly where it is necessary to distribute the load to an underlying weak soil layer or to transfer the load to firm strata through a layer of compressible material or water. In a typical case, the decision to use piling would be made if the site investigation and/or design calculation showed that any other type of foundation will not be sufficient.

Piles may be classified by their manner of installation. Those which displace the soil to accommodate the volume of the pile are called displacement piles or simply as driven piles, while those in which the soil is removed and the void formed is occupied by the pile are called non-displacement piles or simply as bored piles.

Due to drilling machines which normally use helical drills, all bored piles are constructed to have circular cross sections. Bearing capacity of bored piles are determined by the related design formulae, and this type of piling will be out of the scope of this paper just

because it is difficult to change their cross sectional geometry.

A wooden, steel or reinforced pile having different cross sectional areas along its depth is termed as tapered pile (Horvath and Trochalides, 2004). Such piles have their own equations to determine their carrying capacities and they will also be out of the scope of this paper.

The actual method of installing driven piles might be by the blows of a hammer, by vibration or pressure from a jack, the choice being determined by the type of pile, the ground condition and the circumstances of the situation. The essential feature of such piles is the disturbed soil remains in contact with the surface of the newly introduced pile and there is an initial state of stress between the surface of the pile and the surrounding soil resulting from the process of installation.

Suitable cross-section such as square, hexagonal, rectangular or circular was used all around the world. In Iraq, pre-cast reinforced concrete piles having square cross sections are often used in deep beds of soft to

medium clay and silt that have a limited percentage of sand or gravel. The pile is supported in this case mainly by adhesion and to some extent by frictional action to the soil on the surface of the pile shaft. Such piles are termed friction piles (Woods et al., 1962). In firm sands and gravel, end bearing can provide a considerable part of the total resistance, loose sand may provide less bearing, hard clay may provide considerable point resistance, and soft clay practically none.

CARRYING CAPACITY OF DRIVEN PILES

In general, according to Rajapakse (2008) and Tomlinson (1987), the failure load Q of a precast reinforced concrete driven pile in cohesive soils can be determined by the following formula:

Failure load $Q = \text{Load carried on shaft} + \text{Load carried by base} + \text{Self-weight of pile}$

$$Q = C_a \times A_s + N_c \times A \times C_u + \gamma \times D \times A \quad (1)$$

Where C_a = average adhesion between shaft and clay, A_s = surface area of pile shaft, N_c = bearing capacity factor, A = area of pile base, C_u = undrained shear strength at pile base, γ = bulk density of clay and D = depth to pile base.

The weight of the pile is approximately equal to $(\gamma \times D \times A)$. Thus, the surface applied load, P_f causing failure of the pile is given by:

$$P_f = C_a \times A_s + N_c \times A \times C_u \quad (2)$$

For deep soil layers contain silt and clay, as in the case of Iraqi soil, the end bearing capacity will be negligible. Therefore, the failure load of a driven pile could be determined by:

$$P_f = C_a \times A_s \quad (3)$$

The factor C_a - which represent the adhesion between pile shaft and clay- is constant for a given soil property, then the major remaining factor determining the carrying capacity of a driven pile is its surface area. The surface area of any pile is calculated by multiplying its circumferential length by its depth. Therefore, there is a direct relation between a pile carrying capacity and both of its circumference and its length.

GEOMETRICAL CALCULATION

All square cross section driven piles are precasted. Therefore, its cross section can be easily changed according to the designer and that can be simply done by changing its casting moulds.

The typical used sizes- measured in centimeters- are: 28 x 28, 40 x 40 and 50 x 50. The area of a square cross

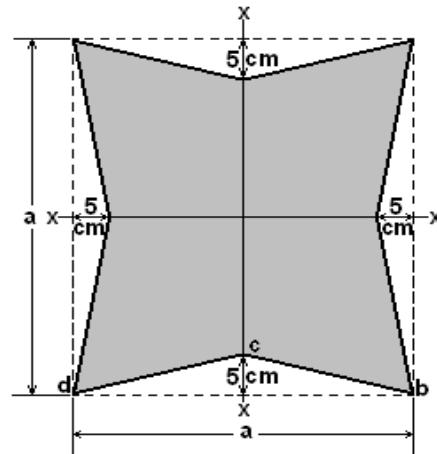


Figure 1. Star shape geometry.

section pile having a side length of 28 cm is 784 cm^2 and its circumference is 112 cm. While an equivalent area of a circular cross section will produce a diameter of 31.6 cm and will give a circumference of 99.25 cm. This means that the circular cross section when used for piling will reduce the carrying capacity of the pile by 11.4% compared with a square cross section pile having the same quantity of reinforced concrete. In other words, if the efficiency of a square cross section pile is 100% the equivalent circular cross section pile will carry only 88.6% compared to it. In spite of the long circumference of rectangular cross section driven piles it is not recommended to use such piles just because of their unequal transverse rigidity which inferiors their resistance to handling, driving and structural loading. The properties of hexagonal cross section driven piles are considered as a combination of the properties of square and circular cross sections.

Based upon the above mathematical facts, a star cross section pile as shown in Figure 1 will be investigated.

The star shape is a modification of a square having a cleavage at each of its four sides. For an equivalent star shape with a square cross section having a side length of 28 cm, the proposed cleavage depth is 5 cm.

To calculate the properties of the star shape cross section, the length of its side (a) can be determined by taking into account that its area is equal to a square having an area of 784 cm^2 .

$$a^2 = 784 + 4 \times 5 \times \frac{a}{2}$$

$$a = 33.44 \text{ cm}$$

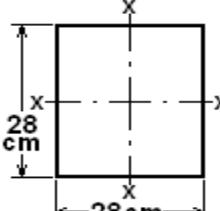
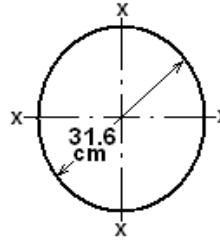
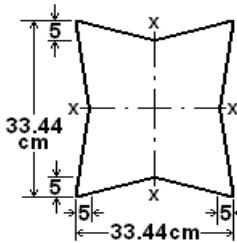
\Rightarrow

For calculating its circumference;

$$cb = \sqrt{5^2 + (\frac{a}{2})^2} = 17.44 \text{ cm}$$

Then its circumference is $= 8 \times 17.44 = 139.6 \text{ cm}$

Table 1. Comparison between the properties of different geometrical cross sections.

Cross sectional geometry	Area (cm ²)	Circumference (cm)	Circumference %	Moment of Inertia I _{xx} (cm ⁴)	Moment of Inertia I _{xx} %
 Square	784	112	100%	51,221	100%
 Circular	784	99.25	88.6%	48,966	95.6%
 Star shape	784	140	125%	58,320	114%

To calculate its moment of inertia about x-x axis:

$$\begin{aligned}
 I_{xx} &= \frac{33.44^4}{12} - 2 \left[\frac{33.44 \times 5^3}{36} + 33.44 \times \frac{5}{2} \left(\frac{33.44}{2} - \frac{5}{3} \right)^2 \right] - 4 \left[\frac{5 \times \left(\frac{33.44}{2} \right)^3}{36} + \frac{33.44}{2} \times \frac{5}{2} \times \left(\frac{1}{3} \times \frac{33.44}{2} \right)^2 \right] \Rightarrow I_{xx} \\
 &= 58320 \text{ cm}^4
 \end{aligned}$$

The above calculation which is tabulated in Table 1 shows that the star shape have the longest circumference of 140 cm compared to 112 cm for the square section, while the circular section gets the shortest circumference of 99.25 cm.

This means that the comparison between the surface area of piles having the same cross sectional area, but with different geometries will yield to the results given in Table 1.

If the circumference of a square pile is considered to have 100% then the star shape pile will be 125%, while the circular one will get only 88.6%.

According to AISC 315-11B (2011), by using the

following formulas for calculating the moment of inertia for each of the three shapes about an axis passing through their Centroid, $bh^3/12$ for the square, $bh^3/36$ for the triangle and $\pi d^4/64$ for the circle, the calculation yield that: the star shape is higher than the square by 14%, while the circular is less than the square by 4.4%.

PILE REINFORCEMENT

Normally a square cross section driven pile is reinforced by 4Φ16 mm steel bars in addition to Φ8 mm ties spaced at 150 mm c/c. This will give a main reinforcement area

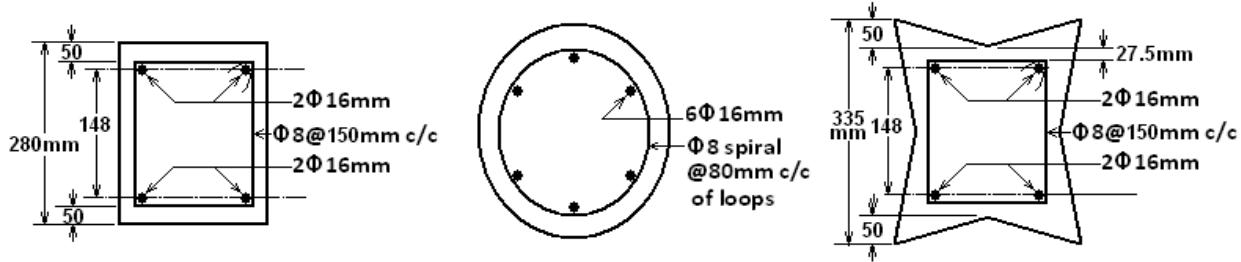


Figure 2. Reinforcement of square, circular and star shape piles.

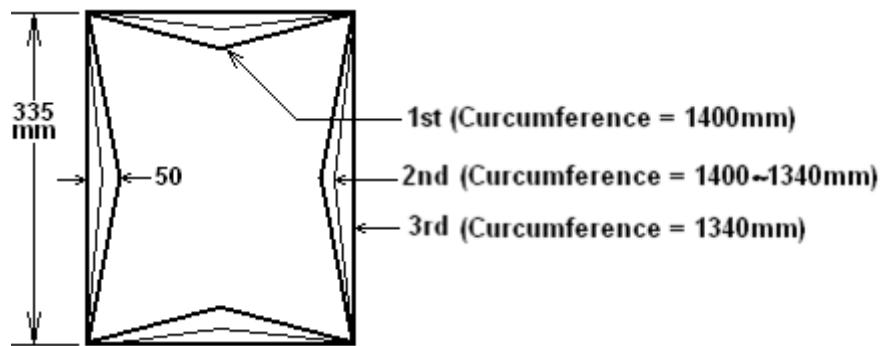


Figure 3. Expected possibilities of failure surface.

of 800 mm^2 . Current codes of practice require using a minimum of $6\Phi 16 \text{ mm}$ bars in addition to $\Phi 8 \text{ mm}$ spiral spaced at 80 mm c/c between its loops to reinforce Circular cross section driven piles. This will give a main reinforcement area of 1200 mm^2 . Figure 2 shows the suggested steel reinforcement detail for the three pile types. It can be noticed that the square and the star shape can be used with less amount of steel reinforcement compared to circular cross section piles.

Concrete cover is increased around the main reinforcement of a star shape but it is reduced, for the ties only, especially near the sides necking (ACI 318-08). For precast concrete pile that is expected to be exposed to earth, as in our case, the minimum cover should not be less than 1.25 in (32 mm) if bars #5 (16 mm) are going to be used. Figure 2 shows that the available cover for certain parts of the ties is 27.5 mm which is less than the required minimum of 32 mm. Taking into account that the main reinforcement will be well protected and the structural action of the ties will not be affected, this violation can be skipped by using proper water proofing coatings.

DISCUSSION

The previous calculation shows that a pile having a star shape cross section is expected to have more contact area with the surrounding soil. The failure surface is

expected to be directly along the contact of the concrete surface and the surrounding soil as shown in Figure 3 and this was considered as a base for the calculation. It might be along the third possible surface which is a square of a side length of 335 mm or in between the previous two possibilities. In all cases, the star shape will have more contact area than a normal equivalent area square section.

Taking into account that the ultimate carrying capacity of a driven pile is evaluated by finding the product of its surface area and its friction with soil which is constant for a certain soil, this will mean that by the same quantity of material a star shape pile will have 25% increase in its ultimate capacity compared to a square section pile and an increase of 36% compared to a circular pile. In other words, it is possible to use star shape driven piles having four fifths the length of square piles.

CONCLUSIONS

The following results have been reached:

1. Circular cross section driven piles are less efficient by 11.4% in ultimate carrying capacity compared to square piles having the same cross sectional area.
2. Square cross section driven piles are less efficient by

20% in ultimate carrying capacity compared to the suggested star shape cross sectional driven piles having the same cross sectional area.

3. The amount of increase of the ultimate carrying capacity of the suggested star shape driven pile is 25% more than that of the current square cross sectional piles.

4. 20% of the length of a driven pile can be terminated if its cross section geometry is changed from the current square to the suggested star shape.

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