The Behavior of Plugged Pipe Piles Strengthened with Biaxial Carbon-Fiber under the Effect of Lateral Loads

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Abstract. This paper presents an experimental study to investigate the behavior of plugged pipe pile strengthened with biaxial carbon fiber under the effect of lateral loads in sand. The change of plug length and incremental filling ratio of pipe pile under static lateral load is considered. The model of piles is embedded in dense sand with different slenderness ratios of pile. In addition, different ratios of confining length of biaxial carbon fiber are used. The results indicated that the ultimate lateral resistance of plugged pipe pile increases with increase of the confining length of carbon fiber.

1. Introduction
The laterally loaded piles have a number of uses as foundations of structures, such as high-rise buildings subjected to wind and earthquake loadings, offshore structures (Mandeel, 2000) [1]. The lateral load capacity of piles depends on many properties of soil and foundations of piles, where the pile head deflection depends on soil type, pile installation, pile flexibility (or pile stiffness). Broms (1964) studied the lateral load of piles in cohesionless soil considering two types of failure of piles. The first type of failure is in the soil and the second type is a flexural of pile by formation a plastic hinge. The transition from a rigid pile to flexible pile in sand occurs at L/D ratio from 12 to 15 with a relative density of 80% (Sharma, 2011) [2].
For a long (flexible) pile, the cumulative of passive resistance is developed at the lower part of the pile is quite high due to that the pile cannot rotate and failure occurs at the point of maximum bending moment. Accordingly, the plastic hinge in the pile occurs. In addition, the mechanism of failure depends on the slenderness ratio (length, L to diameter, D) of pile, type of soil.
The lateral capacity of the pile can be increased by reinforcing the soil or other structural measure, which is primarily enlarge the cross-section area of the upper end of the pile. The carbon fiber is widespread used in structural engineering applications. The carbon fiber has a high tensile strength, where the tensile strength is the maximum stress that a material can withstand while being stretched or pulled before failing.
For composite piles by carbon fiber, very little field information is available on lateral loading behavior. Han and Frost (1999) [3] pointed out that in order to reasonably predict the load deflection response of a laterally loaded composite pile, the shear deformation effects should be taken into account. Fam and Rizkalla (2003) [4] conducted a lateral load test on both the concrete filled with fiber reinforced polymer (FRP) composite and pre-stressed concrete piles.

2. Experimental Work
2.1 The materials
The materials used in this study as follows:
(1) Sand
The physical properties and strength parameter of sand used in this study are presented in Table 1
Table 1: The physical properties and strength parameter of sand

| Physical Properties and Strength Parameter | The Value | Specification |
|-------------------------------------------|-----------|---------------|
| Angle of internal friction (\(\phi\)), deg. | 36.79     | ASTM D3080-03 |
| Specific gravity, (Gs)                     | 2.66      | ASTM D854-07  |
| Maximum dry unit weight, (kN/m\(^3\))      | 18.00     |               |
| Minimum dry unit weight, (kN/m\(^3\))      | 16.10     |               |

2.1 Model of pipe pile

A steel pipe pile (see, Plate 1) with an outer diameter of (20 mm), wall thickness 0.5 mm and different length of pile (360, 420, 480, 540, 600, 660 and 720) mm were used to perform the objectives of this study. The ratio of the length/diameter (L/D) of the piles is used as suggested by Sharma (2011), which is varies between (12 -30).

The free length of the pile above the surface of the soil, \(e\) is 120 mm. The lateral load is applied to the pile with free head pile condition (the pile head is not restraint). Table 2 shows the mechanical properties of the material of the pile.

Table 2: The mechanical properties of pile material

| Property                               | Value    |
|----------------------------------------|----------|
| Modulus of elasticity (N/mm\(^2\))     | 33.33    |
| Minimum ultimate yield strength (N/mm\(^2\)) | 49.40    |
| Minimum yield strength (N/mm\(^2\))    | 41.0     |
2.1.1 Carbon Fiber-Reinforced Polymer (CFRP)

The physical and mechanical properties of the carbon fiber used in this study is shown in Table 3. The carbon fiber is pasted with the pile by a bonding polymer material (2-Part Epoxy Impregnation Resin) which is used for this purpose.

| Technical Data          | Mechanical / Physical Properties |
|-------------------------|----------------------------------|
| Areal Weight            | Laminate thickness 1.0 mm per layer |
| Fabric Design Thickness | Ultimate load 420 KN/m width per layer |
| Fiber Density           | Tensile E-modulus 33.0 KN/mm² (based on typical laminate thickness of 1.0 mm) |

*The properties of the carbon fiber is provided from the manufacturer.

2.1.2 Preparing the piles strengthened with the carbon fiber-reinforced

The following steps describe the procedure to prepare piles strengthened with carbon fiber-reinforced polymer (see, Plate 1):

1. Primer wrapping: The mixed material of 2-part epoxy impregnating resin (mixing ratio component A: component B = 4:1 by weight) primer is applied over the prepared and cleaned surface.
2. Saturate coating: The saturate system used in this work is made of two parts, i.e. resin and hardener. The components are thoroughly mixed for 3 minutes before application.
3. FRP wrapping: The first sheet of saturating (resin) was applied over the primer layer and FRP sheets were then wrapped directly on the surface. CFRP layers are wrapped around the pile with an overlap of the fabric at least 100 mm depending on sika wrap of the perimeter to avoid sliding of fibers during tests and to ensure desired typical strength.
The model of pile confined with 0.5L biaxial carbon fiber is shown in Plate 2.

Plate 2: The model of pile confined with 0.5L biaxial carbon fiber.

2.2 The set-up of the experimental model
The set-up of the experimental model is shown in Plate 3. The lateral loading system consists of horizontal hydraulic jack system with loading screw steel shaft with diameter of 15 mm that employees a lateral force which is applied on the pile cap by using sharpen shaft that gives the ability to provide a point load, The shaft is attached with a load cell to measure the load applied from the jack. The load cell joined between the loading steel shaft (that united with hydraulic jack) and sharpen shaft attached with piles head. The hydraulic jack is programmed to move with a rate changes from very slow movement to moderate movement rate and it can input it manually from the “AC” system to obtain an appropriate rate of movement.

Plate 3: The set-up of the experimental model
2.3 Installation of the pipe pile

Sand with a relative density of 80% is used. The soil is prepared by adding a weight of sand in a container which is determined in advance corresponding to a specific density of soil. The soil is divided into layers; each layer is compacted by a tamping hammer which is employed a uniform distributed blow to get the required density through satisfy a specified thickness of layer. After that, the pile is pressed into the soil in stages, in each stage a 100 mm of the length of pile inserted by using a hydraulic compression jack, so that the free length of pile above the soil surface, ξ to be 120 mm as shown in Plate 4.

![Plate 4: Installation of plugged pipe pile](image)

3. Scale Effects

The scale effects for the small-scale model are considered, which is related to the shear zone formation in the active region directly beneath the footing. Kusakabe (1995) [5] recommended that, a model with a ratio of D/D50 ranging from (50–100) is used to avoid the particle size effect. In this study, the ratio of D/D50 is 60.6, where D is the diameter of pile and D50 is the diameter of soil particles corresponding to percent finer than 50 of grain size distribution.

4. The Behavior of Plugged Pipe Piles Strengthened with Biaxial Carbon-Fiber under the Effect of Lateral Loads

4.1 The Incremental Filing Ratio (IFR)

The soil plug consists in an open-ended pile during the insertion process is a very significant factor in determining of the pile behavior. To determine the degree of plugging of soil, the incremental filling ratio is considered which expresses the increase in soil plug length inside a pipe pile per unit increase of penetration depth of pile in soil and can be expressed as (Iskander, 2010) [6]:

$$IFR\% = \left( \frac{\Delta L}{\Delta D_p} \right) \times 100$$

(1)
where $\Delta L/\Delta D_p$ expresses the increase in soil plug length, per unit increase in penetration depth. The change in IFR for pressed unconfined and confined pipe piles with biaxial carbon fiber installed in sand with a relative density of 80% for different ratios of length/diameter are shown in Figures 1-3.

Figure 1: The values of IFR and soil plug length versus the penetration depth for unconfined pile with L/D=30.

Figure 2: The values of IFR and soil plug length versus the penetration depth for unconfined pile with L/D=30 and fully confined with biaxial carbon fiber.

Figure 3: The values of IFR and soil plug length versus the penetration depth for unconfined pile with L/D=30 and confined with 0.5L of biaxial carbon fiber.
In this study, the changes of the soil plug length and incremental filling ratio, IFR with penetration depth indicates that the open-ended pile is partially plugged. The IFR is about 13% in case unconfined pile, 10% in case of pile confined with 0.5 of the pile lengths and 5% in case fully confined with biaxial carbon fiber. This behaviour can be attribute to that the coefficient of friction tends to increase significantly with an increase in the magnitude of normalized surface roughness. Shaia (2012) [7] showed that, the interface behaviour between fabric reinforced polymer materials and sand depended on the FRP surface roughness, mean particle size (D50) and relative density. Figure 4 shows the soil plug lengths of pipe piles with a length/diameter, L/D of 30 for pile unconfined and confined fully and 0.5L with biaxial carbon fiber. From this figure it can be stated that, the value of plug length decreases with increase the strengthen length with biaxial carbon fiber. Where, the minimum value of plug length occurs in the case of fully confined and this is due to the increasing of the friction resistance along the pile shaft during the installation process. This behaviour can be affecting the end bearing capacity of pile in the case of pile subjected to a combination of vertical and lateral load.

![Figure 4: The soil plug length for pile with length/diameter of 30 unconfined confined and unconfined and confined fully and 0.5L with biaxial carbon fiber.](image)

4.2 The Behaviour of Partially Plugged Pipe Piles Strengthened with Biaxial Carbon-Fiber under the Effect of Lateral Loads

In this study, a total number of 9 models of partially plugged pipe piles are tested under the lateral load according to ASTM D3966 – 07 Specifications [8]. The piles are embedded in dense sand with different ratios of length/diameter and different percent of confining with biaxial carbon fiber. The results of the lateral load-displacement curve for unconfined partially plugged pipe pile under static lateral load are shown in Figures 5 to 11.
Figure 5: Load –displacement curve for unconfined partially plugged pipe pile under static lateral load with L/D=12.

Figure 6: Load –displacement curve for unconfined partially plugged pipe pile under static lateral load with L/D=15.

Figure 7: Load –displacement curve for unconfined partially plugged pipe pile under static lateral load with L/D=18.
Figure 8: Load –displacement curve for unconfined partially plugged pipe pile under static lateral load with L/D=21.

Figure 9: Load –displacement curve for unconfined partially plugged pipe pile under static lateral load with L/D=24.

Figure 10: Load –displacement curve for unconfined partially plugged pipe pile under static lateral load with L/D=27.
Figure 11: Load –displacement curve for unconfined partially plugged pipe pile under static lateral load with L/D=30.

Table 4 show the ultimate lateral resistance of unconfined partially plugged pipe pile under static lateral load with different ratios of L/D. From this table it can be concluded that, the ultimate lateral resistance of partially plugged pipe piles increases with the increasing in L/D.

Table 4: the ultimate lateral resistance of unconfined partially plugged pipe pile under static lateral load with different ratios of L/D.

| Length/Diameter | Ultimate Lateral Resistance (N) |
|-----------------|---------------------------------|
| 12              | 45                              |
| 15              | 65                              |
| 18              | 80                              |
| 21              | 127                             |
| 24              | 179                             |
| 27              | 194                             |
| 30              | 267                             |

The ultimate lateral resistance of partially plugged pipe pile with L/D of 30 embedded in dense sand confined with 0.5L and fully confined with biaxial carbon fiber are 300 N and 330 N, respectively (see, Figures 12 and 13). Accordingly, the ultimate lateral resistance of partially plugged pipe pile fully confined with biaxial carbon fiber is more than that for unconfined partially plugged pipe pile for the same ratio of L/D by 23.59%. This behavior is due to an increase in the stiffness of pile that provided from the biaxial carbon fiber.
5. Conclusions
(1) The Increments Filling Ratio (IFR), which is an indicated of formation a soil plug in an open-ended steel pile, is about 13% in case unconfined pile, 10% in case of pile confined with 0.5 of the pile lengths and 5% in case fully confined with biaxial carbon fiber. This behavior can be attribute to that the coefficient of friction tends to increase significantly with an increase in the magnitude of normalized surface roughness
(2) The ultimate lateral resistance of partially plugged pipe pile fully confined with biaxial carbon fiber is more than that for unconfined partially plugged pipe pile for the same ratio of L/D by 23.59%. This behavior is due to an increase in the stiffness of pile that provided from the biaxial carbon fiber.

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