Axial Cyclic Behavior of FRP Confined Seawater Sea-Sand Concrete Piles

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ABSTRACT

Fiber-reinforced polymer (FRP) composites coupled with seawater sea-sand concrete (SSC) provide an innovative and sustainable solution by replacing the conventional piling materials for the marine infrastructures. This study investigates the axial behavior of FRP composite SSC model piles subjected to cyclic loading of different amplitudes and mean loads levels. The strain along the depth of piles is measured by an advanced distributed optic sensing technique called optical frequency domain reflectometry (OFDR) having a spatial resolution of 1 mm and $\pm 1\mu\varepsilon$ sensing accuracy. Three structural configurations; FRP tube confined and FRP rebars cage reinforced and centered FRP rebar SSC piles ended in rock-socket are investigated in physical models to examine the performance of FRP composites and SSC in pile foundations. The accumulated displacement of model piles under different modes of axial cyclic loading are analyzed and explored in detail. It is found that the accumulation of permanent cyclic displacement increases markedly initially till 30 cycles and then followed a constant trend with increasing cycles passing. Under the same cyclic loading conditions, the FRP tube confined model piles exhibited lower cyclic degradation leading to stable behavior. The FRP tube confined model piles showed higher confinement and axial cyclic capacities compare to those reinforced with FRP rebars. The OFDR sensing technique monitored the localized effects efficiently that how the load is distributed along the length of model piles.

INTRODUCTION

The traditional pile foundations in a harsh marine environment experience severe corrosion of steel, marine borer attacks on the timber piles, and concrete deterioration causing many problems like failure of the structure and huge maintenance costs(Iskander & Hassan, 1998; Iskander & Stachula, 2002). Apart, the consumption of large quantities of river sand and fresh water in the construction industry poses a major concern for future developments and environmental sustainability. However, steel reinforced concrete poses no compatibility due to chloride ions in sea water and sea sand which can enhance corrosion problems. Therefore fiber-reinforced polymer (FRP) composites coupled with seawater sea-sand concrete (SSC) provide an innovative and sustainable solution by replacing the conventional piling materials for the marine infrastructures.

Pile foundations are usually subjected to cyclic loadings caused by wind, water currents, waves, earthquakes, traffic loads, and ice sheets. Cyclic loadings are variable and repeated in nature with a different range of magnitudes and cycles (Jardine et al., 2013) The long-term axial cyclic behavior of piles showed that the accumulated settlement of piles largely depends on the cycling loading parameters (SharnoubyM.M. & NaggarM.H., 2012; Buckley et al., 2018). Although numerous research work has been carried out on cyclic response of piles in sand, chalk, and soft soils, the behavior of piles ended in rock-socket under cyclic loading is rarely reported. Apparently, there is necessity of in-depth study of cyclic loading tests on piles in rock-socket, based on systemic tests to provide guidance and potential predictive measures.

Traditionally, strain measurements for piles foundations are carried out by strain gauges and vibrating wire extensometers which provide strain values at certain points resulting in less reliable strain profile (De Battista et al., 2016). However, distributed fiber optic sensors (DFOS) have overcome the strain measurement limitations providing continuous information along the whole length of fiber. Many researchers have applied typical Brillouin optical time-domain reflectometry (BOTDR) based DFOS having less spatial resolution in geotechnical applications such as monitoring piles, tunnels, pipelines, natural slopes, retaining walls, and dams (Soga, 2014; Zhang et al., 2015). A novel sensing technique with highest spatial resolution and accuracy called optical frequency domain reflectometry (OFDR) has been adopted in this study. The OFDR sensing technique was used to monitor the geogrid deformations of a laboratory model slope with smart geogrids under various loadings (Sun et al., 2020). Similarly the load transfer curves and localized strain variations of a continuous flight auger (CFA) pile were monitored by OFDR optic fibers (Bersan et al., 2018).

This study examines the cyclic behavior of FRP-SSC composite model piles ended in rock socket using a novel distributed sensing technology named OFDR possessing a higher spatial resolution of 1mm and high sensing accuracy of ±1με. The physical model piles were subjected to cyclic loadings of different mean loads and amplitudes to investigate the accumulation and degradation of permanent cyclic displacement with cycles. For future design and risk assessment considerations, the results of this study will assist the geotechnical engineers.

EXPERIMENTAL PROGRAM

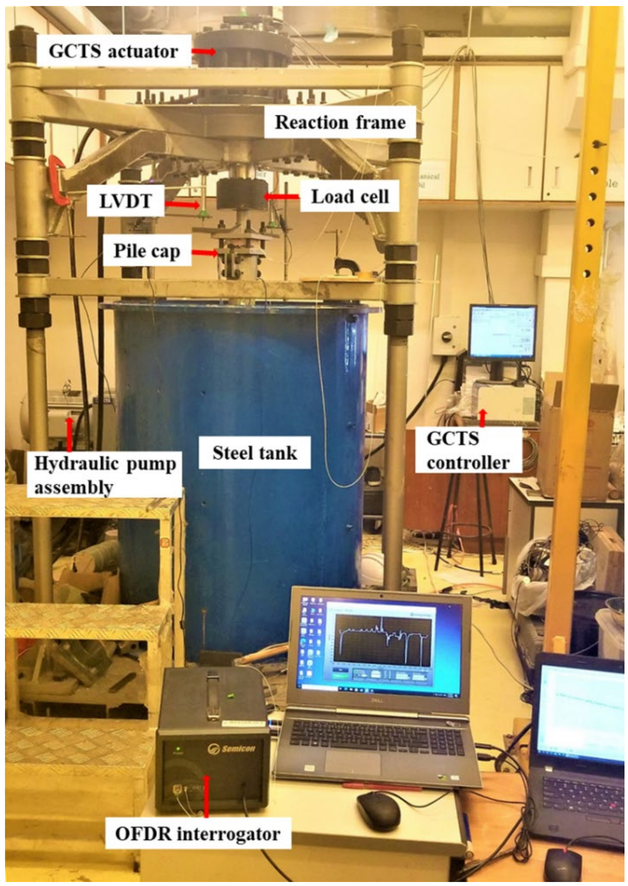
Setup and Design of Physical Model piles

For this study a physical model was designed consisting of hydraulic loading actuator (GCTS, USA) that can apply both static and cyclic loads axially on pile head as shown in Figure 1(a). Model piles were constructed in the steel tank having drilled rock with socket depth of 150 mm and 100 mm diameter. The length to diameter ratio of rock socket was kept 1.5, falling within the range of common geotechnical engineering practices (Ng et al., 2001).

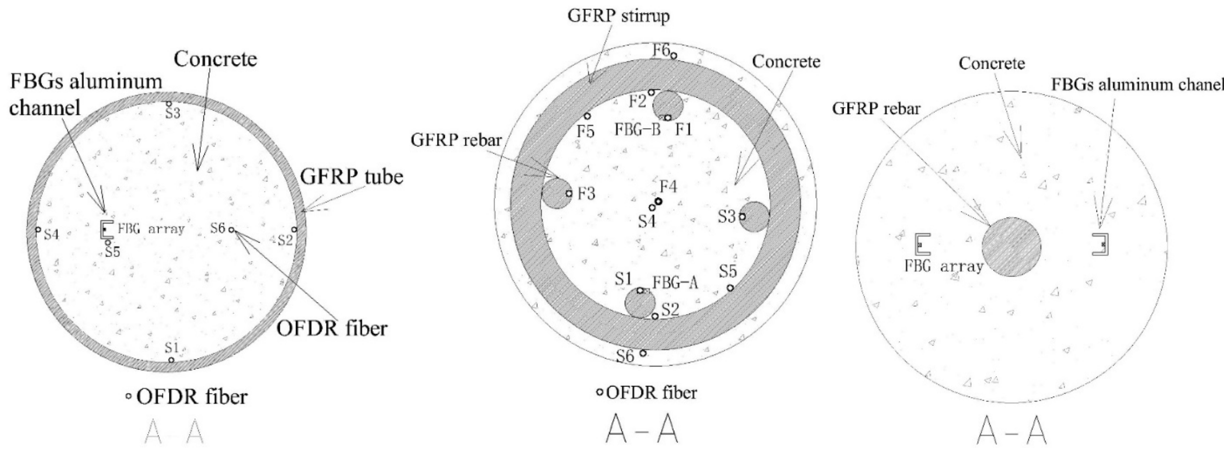
A total of four model piles with different structural configurations, 1450 mm in length and 100 mm in diameter were modelled and tested in this study. Pile 1 and Pile 2 were confined with 3.5 mm thick GFRP tube, Pile 3 was reinforced with 9.5 mm diameter rebars, and Pile 4 has a centered rebar of diameter 19 mm as shown in Figure 1(b). The GFRP tube serve as a formwork for first two model piles and SSC was cast in it while for third pile the rebar cage was first fabricated and then fixed in the socket followed by casting concrete inside.

The model piles were instrumented with an advanced distributed optical fiber sensing (DOFS) system to measure the deformation along the pile depth based on Rayleigh backscattering through OFDR sensing technique. The OFDR interrogator used in this study have a spatial resolution of 1 mm with measuring accuracy of ±1.0 microstrain. Four OFDR sensing fibers were installed longitudinally on GFRP tube for Pile 1 and Pile 2 with two fibers embedded in the SSC shown in Figure 1(c). For Pile 3, fibers were installed on the rebars and within the SSC, as shown in Figure 1(c).

In addition, multiplexed FBGs were also instrumented, due to high data acquisition frequency for cyclic loads.



(a)



(b) **(c)** **(d)**

Figure 1. Physical model system: (a) setup of the whole physical model system; (b) Pile 1 or Pile 2; (c) Pile 3 ; and (d) Pile 4

TESTING PROGRAM

The model piles were subjected to a series of cyclic loadings with different cyclic amplitudes and mean loads, summarized in Table. 4. Generally, offshore pile foundations experience cyclic loads with frequencies ranging between 0.0001 to 0.1 Hz and cycles from 10 to 10^5 (Puech, 2013). The frequency adopted in this study was 0.01 Hz with 100 cycles for each loading case. The model piles were unloaded after each stage of cyclic loading and then subjected to axial monotonic compression under the load control condition till the failure.

Table 1. Cyclic loading program of the model piles

Test pile	*Test Code	Mean Load Q_{mean} (kN)	Cyclic amplitude Q_{cyc} (kN)	Cycles applied N	Post cyclic compression capacity Q_{us} (kN)	Sinusoidal frequency (Hz)
Pile 1	P1.CY1	60	30	100	210	0.01
	P1.CY2	120	30	100		
	P1.CY3	120	45	50		
	P1.CY4	180	30	7		
Pile 2	P2.CY1	60	30	100	266	
	P2.CY2	120	30			
	P2.CY3	120	45			
	P2.CY4	180	30			
Pile 3	P3.CY1	60	30	100	213	
	P3.CY2	120	30			
	P3.CY3	120	45			
Pile 4	P4.CY1	60	30	100	239	0.2

*Test code (PX.CYN), where PX represents pile name (P1, P2, P3, P4) and CYN shows number of cyclic test (N=1, 2, 3, 4).

RESULTS AND DISCUSSIONS

Cyclic Parameters and Criteria

Under cyclic axial loading conditions, the behavior of piles driven in sand, clays, and chalk has been classified as stable, meta stable, or unstable based on a specific stability criterion (Jardine & Standing, 2012; Tsuha et al., 2012; Buckley et al., 2018). P1.CY4 was considered unstable, P1.CY1, P2.CY1, P3.CY1 and P4.CY1 have stable response while the remaining eight cyclic stages were appeared to have metastable behavior. The post-cycle monotonic static compression capacity of the corresponding model piles was used to normalize the cyclic loading characteristics.

Permanent accumulated cyclic displacement of model piles

The accumulated cyclic displacement "u_{acc}" was calculated based on the formulations provided in the study (Rimoy et al., 2013). For the cyclic tests on each model pile, the accumulation of pile-head permanent cyclic displacement, u_{acc}, was plotted against the number of cycles, *N*. A constant gradient fitting line is plotted for the cyclic tests for comparing accumulation having a linear trend given as:

$$u_{acc} = AN + B \quad (1)$$

where *A* and *B* are non-dimensional fitting parameters. It was observed that in the cyclic stable tests (Figure 2), stable and low accumulation of the displacements were recorded with a non-linear gradient for the first 20 cycles. After $N > 30$, the rate of accumulated displacement follows the constant gradient fitting line with negligible deviation from it afterward. Initially for $N < 20$, the accumulation rate was as high as 0.02mm/cycle and then followed a steady rate of 0.01mm/20 cycles for $N > 30$. In the metastable tests (Figures 3 and 4), initially the rate of permanent displacement accumulation was higher for $N < 30$, and afterward, it followed a constant gradient fitting line of 0.03 mm/20 cycles. However, P2.CY2 and P2.CY3 metastable cyclic tests showed a slow rate of permanent displacement accumulation comparatively. A metastable cyclic test, P2.CY4, as shown in Figure 5, initially led to a very sharp rate of permanent accumulated displacement for the first 10 cycles. The accumulation non-linearly increased till 40 cycles and then followed a constant gradient fitting line for $N > 40$ with the rate of 0.034 mm/ 20 cycles. During the unstable cyclic test P1.CY4 the displacement accumulation rate was sharp led to failure of the model pile in 7 cycles.

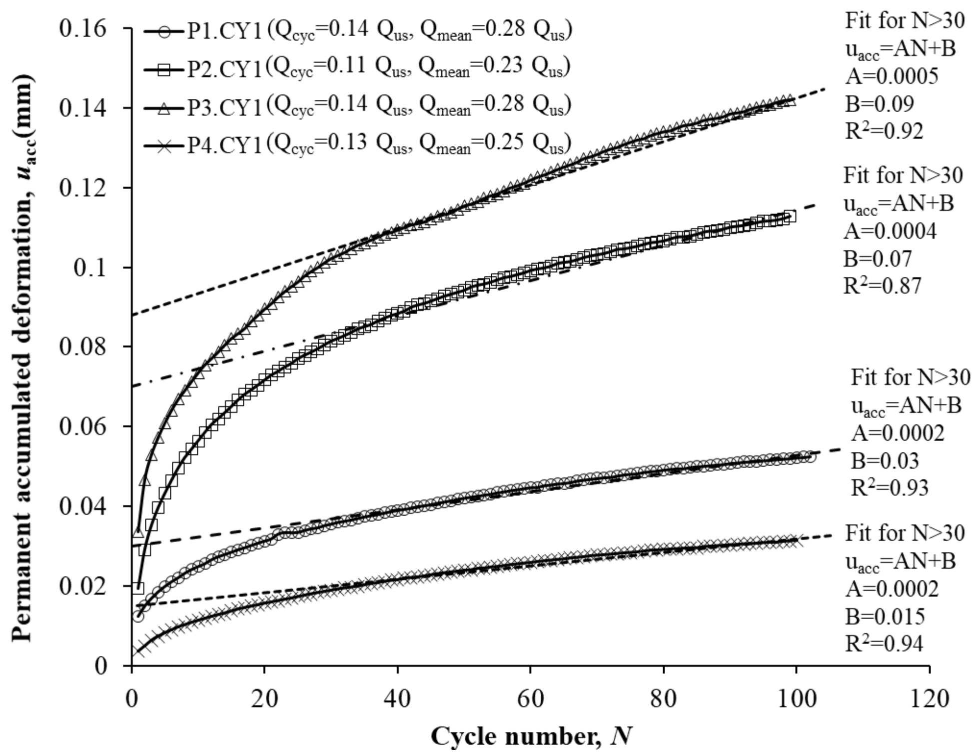


Figure 2. Accumulation of permanent cyclic displacement behavior for stable cyclic tests

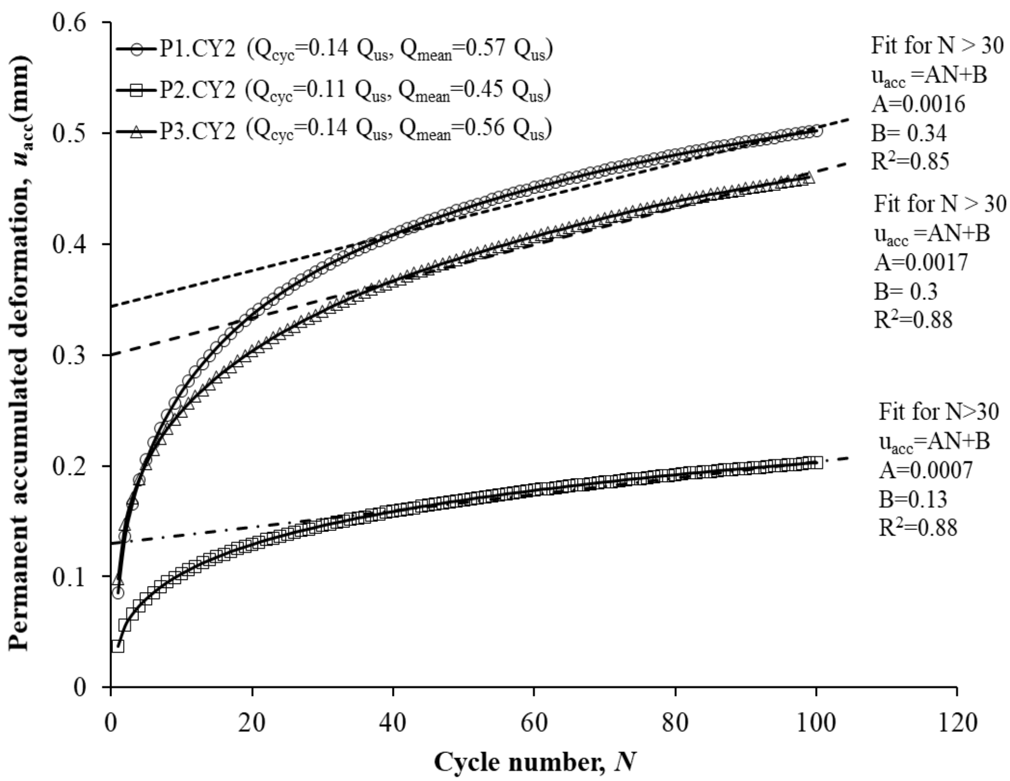


Figure 3. Accumulation of permanent cyclic displacement behavior for metastable cyclic tests

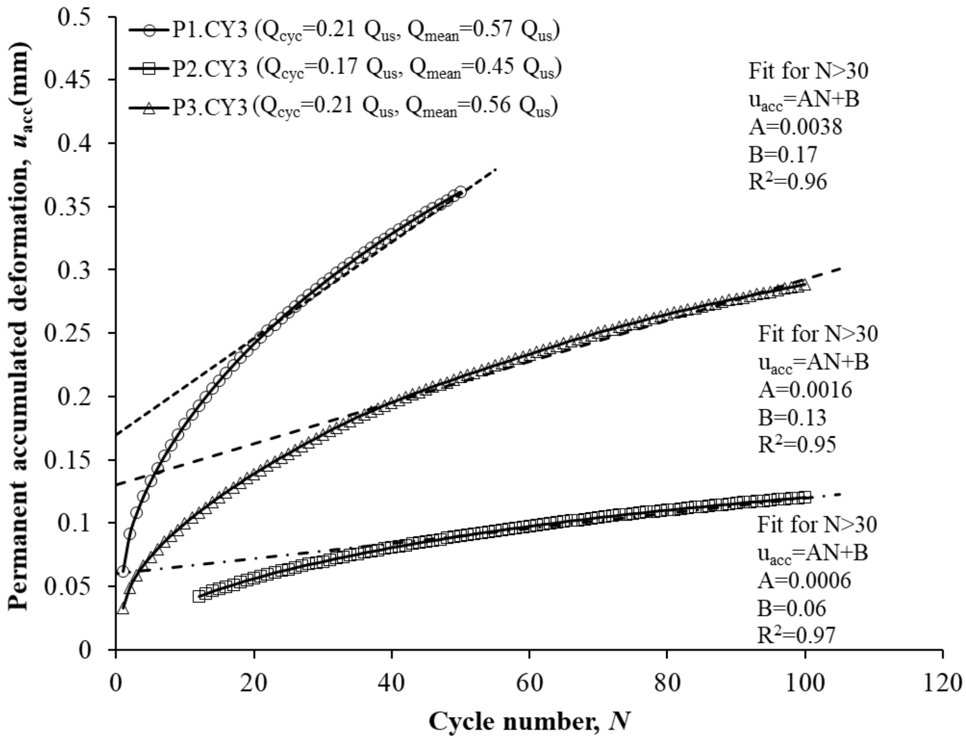


Figure 4. Accumulation of permanent cyclic displacement behavior for metastable cyclic tests with higher Q_{cyc}

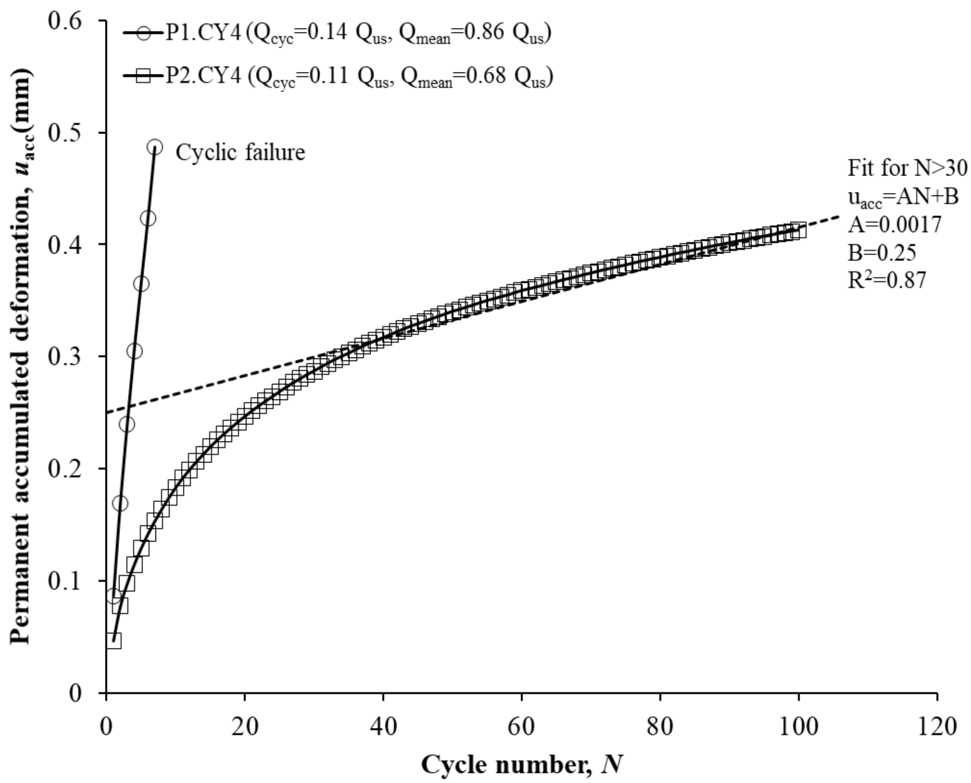


Figure 5. Accumulation of permanent cyclic displacement behavior for unstable/metastable cyclic tests

CONCLUSION

Pile foundations must be durable, economical, and long-lasting in order to guarantee the structural integrity of infrastructures. This study describes a series of axial cyclic loading tests performed on FRP composite SSC physical model piles in rock-socket under varying cyclic amplitudes and mean loads. For monitoring the accumulation of permanent cyclic displacement of the physical model piles, OFDR and FBG sensing technologies were used. It was found that the permanent cyclic displacement responses of model piles are influenced by normalized cyclic loading levels. For stable, metastable, and unstable tests, the load-displacement behavior is highly nonlinear in the first 20, 30, and 40 cycles, respectively. For $N > 30$, cyclic displacement accumulation was significant in the initial cycles and then followed a constant gradient trendline for subsequent cycles, which can be incorporated in numerical models to predict the behavior of the same type of piles. Further in-depth study is required to investigate the potential behavior for large number of cycles under a more diverse set of cyclic load levels.

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