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Centrifuge Modeling of Axial Load–Displacement Behavior of Vertical GFRP and Steel Piles in Sand

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ABSTRACT: Fiber-reinforced polymer (FRP) piles are increasingly considered as alternatives to steel piles in corrosive environments; however, their axial load–displacement behavior remains insufficiently documented. This study presents results from a geotechnical centrifuge testing program conducted at New York University Abu Dhabi comparing the axial response of vertical glass fiber–reinforced polymer (GFRP) and steel pile models embedded in sand. Axial compression loads were applied, and pile head displacements were measured continuously. A single representative load–displacement comparison is presented to highlight the global response. The results show that, for the same applied load, GFRP piles exhibit reduced settlements relative to steel piles, indicating enhanced mobilization of axial resistance. The findings provide experimental insight into the axial performance of GFRP piles and support their evaluation for vertical load-bearing applications.

1 INTRODUCTION

Steel piles are widely used in deep foundation systems due to their high axial capacity and established design methodologies (Tomlinson, 2008). In aggressive environments, however, corrosion can adversely affect durability and increase maintenance demands, motivating interest in alternative pile materials (Hannigan et al., 1998).

Glass fiber–reinforced polymer (GFRP) piles offer high corrosion resistance and favorable durability characteristics, but their lower elastic modulus and distinct mechanical behavior compared to steel may influence axial load–displacement response (Bank, 2006). Geotechnical centrifuge modeling provides a controlled framework for investigating pile–soil interaction under prototype stress conditions (Schofield, 1980; Taylor, 1994). This study presents centrifuge test results comparing the axial load–displacement behavior of vertical GFRP and steel pile models embedded in sand, with emphasis on global pile head response.

2 EXPERIMENTAL PROGRAM

The centrifuge tests were conducted using the geotechnical centrifuge facility at New York University Abu Dhabi, which has an effective radius of 5 m and a payload capacity of 260 g·tons. All tests were performed at an acceleration level of 20 g to reproduce prototype stress conditions.

The soil used in the experiments was silica standard sand. The sand bed was prepared in a dry condition using air pluviation to achieve a uniform deposit with a target relative density of 40%. Uniformity of the soil profile across pile locations was verified using cone penetration testing (CPT).

The model piles represent a prototype pile diameter of 300 mm. Both steel and glass fiber–reinforced polymer (GFRP) piles had identical outer diameter, embedded length, overall geometry, and a common steel pile tip mechanically attached to each pile, ensuring identical tip geometry and consistent end-bearing conditions.

The steel piles were tested as hollow circular sections, whereas the GFRP piles were hollow tubes filled with cement paste prior to installation to achieve axial rigidity (EA) comparable to that of the steel piles. Equivalence of axial stiffness between the two configurations was verified through independent axial compression testing using a Universal Testing Machine (UTM).

Pile installation was carried out at 1g by vertical driving using identical procedures for both pile types. Following installation, axial compression tests were performed under centrifuge conditions using incremental loading, with pile head load and displacement measured continuously.

3 LOAD-DISPLACEMENT BEHAVIOR PROGRAM

Figure 1 shows the prototype-scaled axial load–displacement response of vertical GFRP and steel pile models obtained from centrifuge testing under axial compression. Two nominally identical tests are presented for each pile type, demonstrating good repeatability.

For any given applied load, the GFRP piles consistently exhibit smaller pile head displacement than the steel piles, indicating higher mobilized axial resistance under load-controlled conditions. At low load levels, both pile types display similar initial stiffness, consistent with the intentional matching of pile geometry and axial rigidity (EA). With increasing load, the separation between the responses becomes more pronounced, with GFRP piles maintaining reduced settlements relative to steel piles.

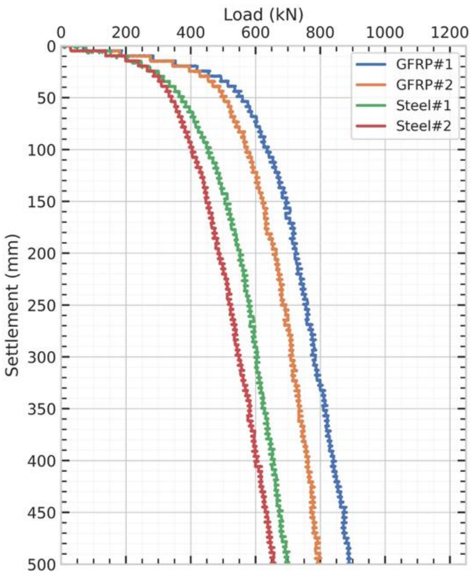

Figure 1. Axial load–displacement response of vertical GFRP and steel pile models.

4 DISCUSSION

Because pile geometry, tip conditions, installation procedure, and axial rigidity were intentionally matched, the observed differences in response can be attributed primarily to pile–soil interface behavior. For the same applied load, the GFRP piles consistently exhibited smaller axial displacements than the steel piles, indicating enhanced mobilization of shaft resistance.

This behavior is attributed to differences in surface characteristics, with the rougher GFRP surface promoting increased interface friction and soil interlocking compared to steel. Similar interface effects have been highlighted in recent studies (Ziogos et al., 2023). The results demonstrate that, when stiffness and geometry are controlled, pile material and surface properties can significantly influence axial load–displacement response in sand.

5 CONCLUSIONS

The following conclusions are drawn from the centrifuge test results:

- For the same applied axial load, GFRP piles exhibited consistently smaller settlements than steel piles.
- Matching geometry, embedment, tip conditions, and axial rigidity isolated pile–soil interface effects.
- The improved performance of GFRP piles is primarily attributed to enhanced shaft friction associated with surface roughness.

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