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Wave equation analyses of tapered FRP–concrete piles in dense sand

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Abstract

Fiber-reinforced polymers (FRP)–concrete composites provide an attractive alternative to conventional pile materials such as steel, concrete and wood by improving the durability of deep foundations. In the current study, FRP tubes with different taper angles are filled with self-consolidating concrete (SCC) and driven into dense sand that is enclosed in a large pressurized soil chamber. Driving tests are conducted on FRP–SCC composite piles to determine how the pile material and geometric configuration affect its driving performance. Dynamic data is employed to determine the soil parameters in the TNO model (i.e., soil quake and damping constant) using the DLTWAVE signal-matching program. The driveability of FRP–SCC and traditional pile materials is compared using the wave equation analysis program PDPWAVE. The experimental data and the wave equation analyses indicate that the taper shape has a favourable effect on the driveability and static resistance of piles. It is also found that the driveability of FRP–SCC composite piles is similar to that of conventional prestressed concrete and steel piles. However, empty FRP tubes required a much higher driving energy. Their low flexural resistance along with risk of buckling can hinder their driveability in different soil conditions.

Keywords: Fiber-reinforced polymers; Wave equation; Self-consolidating concrete; Tapered piles; Pile foundation; Durability; Large-scale modeling; Dense sand

1. Introduction

Fibre-reinforced polymers (FRP) offer a potential solution to the problems associated with corrosion of steel, degradation of concrete and marine borer attack of timber piles. However, their main disadvantages are their initial high cost and lack of design tools for predicting their behaviour during installation and subsequent service life. It is anticipated, however, that the growing use of FRP composites and development of low-cost production techniques will make them increasingly more competitive.

An efficient pile foundation can be achieved by using a system of FRP shell filled with concrete. The FRP shell provides external reinforcement, assures a stay-in-place formwork, protects the concrete core from damage, ensures a long life cycle, and improves durability in harsh environments. The concrete core provides compressive load capacity and dimensional stability of the shell to develop its full flexural capacity without local buckling. Efficiency of FRP composite piles can be further enhanced through optimizing their configuration by using taper piles. The much higher compressive resistance of tapered piles compared to conventional cylindrical piles has been long recognized [1–5].

The driveability of conventional piles can be predicted using wave equation analysis [6]. Wave equation analysis is typically used for selecting/approval of driving equipment (i.e., hammer components, hammer cushion, driving head, and pile cushion) and ensuring that the driving stresses will not exceed the strength of the pile material. This can ensure that driving equipment be selected such that piles can be driven with reasonable effort to the predetermined embedded depth without damage. Several computer programs based on wave equation analysis are widely used such as WEAP [7]; TT1, developed by the Texas Transportation Institute and Texas A&M University [8], and TNOWAVE [9]. However, FRP composites have

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different properties than those of conventional pile materials and are not considered in most available software packages. Therefore, the input parameters for FRP composites should be calibrated in order to facilitate conducting driveability studies using the available software.

Pando et al. [10] performed full-scale pile installations and load tests using FRP tubes filled with concrete and prestressed concrete piles. Their results showed that both pile materials exhibited similar driving behaviour and axial capacity in compression. Mirmiran et al. [11] conducted field installations of empty FRP tubes, FRP–concrete piles, and spliced tubes using conventional driving at the pile head. They concluded that FRP–concrete composite piles presented a valuable solution for bridge substructure. Iskander et al. [12] conducted a parametric study using wave equation analysis on several composite materials. They concluded that the driveability of composite materials depends on their specific weight and elastic modulus. Using wave equation analysis, Ashford and Jakrapiyanun [13] found that the driveability of FRP piles compared favourably with that of steel pipes and precast prestressed concrete piles.

A large-scale testing facility (pressure chamber) was built at the University of Western Ontario to install and test pile segments at presubscribed combinations of vertical and radial pressures, simulating stresses within the soil at specific depths. FRP–concrete piles were installed at radial/vertical pressures of 30/60 kPa to represent a pile segment embedded at 4.0 m depth. The objectives of this paper are: (1) to experimentally evaluate the input parameters for driveability analyses of FRP composite cylindrical piles; (2) to determine the factors that influence the driveability of tapered piles; (3) to determine the optimum hammer to be used for FRP concrete composite sections; and (4) to validate the use of TNOWAVE for predicting the static resistance of tapered piles.

2. Experimental arrangement

Four instrumented FRP–concrete composite piles were used in this study. The piles were composed of a FRP shell filled with self-consolidating concrete (SCC). The SCC provided a cost-effective infill, filled formwork without need for viberator, and assured the structural integrity of piles [14]. The fresh concrete properties are as follows: unit weight of 2420 kg/m^3, slump of 240 mm, and slump flow of 550 mm.The 7- and 28-day compressive strengths of the concrete are 42 and 58 MPa, respectively. Three piles had different taper angles, while the fourth one was cylindrical with similar length and a diameter approximately equal to the average embedded diameter of the tapered piles. Tapered piles T1, T2 and T3 had taper angles of $\alpha = 0.53^\circ$, 0.71° and 1.13°, respectively. Table 1 presents the details of pile geometry and composite material properties. In general, the model pile diameter was made as large as practical to represent interface characteristics and capture the taper effect.

The soil bed was air-dried Fanshawe Brick sand of fine subround to round particles with $D_{50} = 0.26$ mm. The soil bed was prepared using a raining technique to achieve consistent and uniform dense soil samples with relative density of about 90%. The peak frictional angle, ϕ_p, and residual frictional angle, ϕ_r, determined from direct shear tests under normal stresses ranging between 25 and 200 kPa were 37° and 31°, respectively.

The piles were driven and tested in a pressure chamber with 1.34 m inside diameter and 1.52 m height. The pressure chamber had radial and vertical air bladders that can be pressurized to achieve the desired radial and vertical confinement pressures. Sakr et al. [15] gave a detailed description of the pressure chamber and experimental setup. Applied radial/vertical boundary pressures of 30/60 kPa were maintained to represent a soil layer at an embedment depth of about 4.0 m in normally consolidated sand ($K_0 = 0.5$). Fig. 1(a) shows a schematic of the experimental arrangements, while Fig. 1(b) shows an oblique view of the test setup. All model piles were installed to an embedded length of 1.2 m using a single-acting hammer with a 1.0 kN ram falling through a distance of 1.2 m onto a 51-mm-thick plywood cushion. The pile driver was composed of a mounting frame, electric motor and three-piece hammer. The shaft of the motor was connected to a lifting mechanism, which was fitted with lifting arms that could be adjusted to change the drop height. The motor lifted the ram to the selected falling height, and the hammerhead fell to induce an impact on the hammer components.

Table 1
Geometry and properties of model piles

Pile ID	Taper angle α (°)	Diameter (mm)			Thickness t_s (mm)	Length l (mm)	Composite modulus of elasticity (MPa)	Specific weight (kN/m^3)
		d_t	d_b	d_a				
Sc	0.0	162.4	162.4	162.4	6.00	1524	31,860	24.30
T1	0.53	170.0	198.0	184.0	9.8	1524	33,200	24.69
T2	0.71	159.0	197.0	178.0	7.8	1524	33,150	24.51
T3	1.13	155.0	215.0	185.0	8.2	1520	33,150	24.52

d_t model diameter at the pile toe; d_b model diameter at the pile head; d_a average diameter of the model pile shaft; t_s thickness of pile wall.