Computers and Geotechnics 87 (2017) 178–187

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Research Paper

Performance of geosynthetic-reinforced granular piles in soft clays: Model tests and numerical analysis

Murtaza Hasan *, N.K. Samadhiya

Department of Civil Engineering, Indian Institute of Technology Roorkee, Roorkee 247667, Uttarakhand, India

ARTICLE INFO

Article history:
Received 31 July 2016
Received in revised form 9 December 2016
Accepted 21 February 2017

Keywords:
Stone columns
Geotextile
Geogrid
Plaxis 3D
Soft clays
Numerical analysis

ABSTRACT

The laboratory model tests and numerical analyses have been performed on reinforced granular piles installed in very soft clay. The granular piles were reinforced with geosynthetic in the form of vertical encasement, horizontal strips and combined vertical-horizontal reinforcement. The short term-displacement control model tests were carried out either only a granular pile loaded or with an entire area loaded. The laboratory results in the form of vertical load intensity-settlement behaviour were compared with that obtained from FEM software, PLAXIS 3D. The results indicated significant improvement in ultimate load intensity and stiffness of treated ground due to inclusion of geosynthetic.

1. Introduction

Granular piles (also known as stone columns) have been commonly installed in grounds to improve the load bearing capacity, to reduce settlements and to increase the rate of consolidation. The applications of granular piles include the support of embankments, liquid storage tanks, raft foundations and other low rise structures [1–5]. The load carrying capacity of the granular piles depends on the lateral confining pressure from the surrounding soils. In very soft clays, granular piles do not achieve significant load carrying capacity due to low lateral confinement. Therefore granular piles of additional confinement are needed for the better performance. In recent years, geosynthetic reinforced granular piles have been successfully adopted in very soft soils throughout the world. Vertical encased granular piles have several advantages like increased stiffness of pile by mobilization of hoop stress in the reinforced material, preventing the loss of stones into the surrounding soft clay, preserving the drainage and frictional properties of the stone aggregates. Van Impe and Silence [6] were probably the first who thought of encasing the granular piles by geosynthetic. The laboratory and small scale model tests have conducted on vertical encased granular piles by various researchers [7–15]. Murugesan and Rajagopal [8] found improvement in load carrying capacity of the granular piles due to encasement. The effect of encasement was found to decrease with increase in the diameter of the granular pile. Numerical analyses have performed by various researchers on geosynthetic encased granular piles [7,16–19]. Many authors [20–22] also performed field scale load tests on vertical encased granular piles. The reinforcement in the form of horizontal strips, placed at regular spacing in granular piles increase load carrying capacity of improved ground. Granular piles reinforced with horizontal strips control bulging by mobilising frictional resistance between strips and stone aggregates [11,23–25]. Sharma et al. [23] investigated the effect of the number of geogrid layers and the spacing between them on the load carrying capacity of granular piles.

The reinforcement effect in form of either encasement or horizontal strips has been very well establish through various laboratory studies, field applications and numerical analyses. Generally, only one type of reinforcement (encasement or horizontal strips) has been dealt with. Enough literature is not available on assessment of improvement in the load carrying capacity of the granular piles reinforced with bothy encasement and horizontal strips. Therefore in the present study, combined encased-horizontal stripped granular piles have been installed in very soft clay to investigate the qualitative and quantitative improvement in the ultimate load intensity of granular piles, and stiffness of improved ground. The laboratory model tests were conducted on unreinforced, vertical encased, with horizontal strips and combined vertical-horizontal reinforced granular piles. Numerical analyses

---

* Corresponding author.
E-mail addresses: murtazadce@gmail.com (M. Hasan), nksamfce@iitr.ac.in (N.K. Samadhiya).

http://dx.doi.org/10.1016/j.compgeo.2017.02.016

have also been carried out on granular piles by using finite element software; PLAXIS 3D. The parameters included in this study are shear strength of clay, reinforcement, encasement stiffness and length of granular piles. The ultimate load capacity of granular piles has been found to increase with increase in the depth of encasement [8,12]. In field studies, various authors [20–22] also provided geotextile encasement throughout the length of granular piles. Therefore in the present study, encasement and horizontal strips up to full length of granular piles have been adopted.

2. Experimental programme

The outline of experimental programme is given in Table 1. Unit cell idealisation, by assuming piles in a triangular pattern, was adopted to simplify the design of the apparatus needed to assess the behaviour of an interior granular pile in a large group of piles. Various researchers [3,8,26] have used unit cell concept in their experimental investigations.

The laboratory model tests were carried out on 75 mm diameter single floating and end bearing granular piles. The length of granular piles was kept as 5*d* (375 mm) in case of floating piles and 7*d* (525 mm) for end bearing piles, where *d* is the diameter of the pile. The granular piles were installed in very soft clay bed in a 200 mm diameter and 525 mm high cylindrical tank. Undrained shear strength (c_u) of the very soft clay was kept close to 5 kPa throughout the experimental work. Geotextile and geogrid were used for vertical encasement and horizontal strips respectively. Circular strips of geogrid having diameter 10 mm less than the granular piles were placed over the entire length of granular piles. These strips were placed at three different centre to centre spacing (S) of 25 mm ($d/3$), 50 mm ($2d/3$) and 70 mm ($\approx d$). First geogrid strip in each case was placed 25 mm below the loading plate.

2.1. Modelling considerations

The single granular pile behaviour with unit cell concept simulates the field behaviour for an interior pile when large number of piles is simultaneously loaded. In the present study, the dimensions are reduced by an appropriate scale factor to simulate the behaviour of granular piles installed in the field. Following parameters were considered to be scaled down: (i) ratio of granular pile diameter to unit cell diameter, (ii) ratio of length to diameter of granular pile, (iii) ratio of pile diameter to aggregate size and (iv) tensile strength of geosynthetic materials. Granular pile spacing broadly varies in the range of 2–3 times the diameter of the pile. Since the equilateral triangular pattern gives the densest packing, hence the granular piles have been assumed to be installed in the same pattern as well as the in same spacing. The area replacement ratio, A_r (ratio of the area of the granular pile to the total area within the unit cell) and corresponding centre to centre spacing were kept 14% and 2.5*d* respectively. In the field, the ratio of length to diameter (l/d) of granular pile is varied from 4.5 to 20 whereas in the present study the ratio l/d is kept from 5 to 7, where l is length of pile. In practice, granular piles are constructed in typical diameters (d) varying between 0.6 m in case of stiff clays to 1.1 m in very soft clays and lengths ranging from 5 to 20 m [27]. Well graded stones aggregates of size (k) 2–75 mm are used, so that the ratio d/k lies typically in the range of 8 and 550 [28]. The pile diameter used in the model test was 75 mm. The particle size of crushed stones was kept between 2 mm and 6.3 mm, so that the ratio of d/k in model test lies between 8 and 45. In practice, the tensile strength of geosynthetic materials used in granular piles is kept up to 400 kN/m and stiffness is varied from 1000 to 4000 kN/m [12]. Tensile strength of geosynthetic materials were also reduced as per scaling laws proposed by Iai [29], the relationship between prototype-scale reinforcement stiffness (J_P) and model-scale stiffness (J_m) can be calculated as $J_P = J_m\lambda^2$, where $1/\lambda$ is the model scale. In the present study, $1/\lambda$ is equal to 1/10 therefore stiffness was kept typically in the range of 10–40 kN/m. For laboratory model tests, various researchers [9–12] used tensile strength of geosynthetic material in the range of 1.5–20 kN/m. Geotextile and geogrid having tensile strength of 4.4 kN/m and 7.96 kN/m respectively were used in the present laboratory investigation. Reinforced granular piles are commonly used in soft clayey soils (undrained shear strength less than 7 kPa) to control lateral confinement [11,12,19]. Undrained shear strength of clay in the present study has been kept close to 5 kPa.

2.2. Materials properties

The dried clay, classified as CI as per IS: 1498:2000 [30] was converted into fine powder by grinding and stored in air dried room. The physical properties of clay are presented in Table 2.

The crushed granite aggregates in sizes ranging 2–6.3 mm were used to construct granular piles. The maximum and minimum dry unit weights of the aggregate are 15.04 kN/m^3 and 13.41 kN/m^3 respectively. The relative density of stone aggregates in granular piles was considered 70% to ensure negligible bulging during construction of pile. The dry unit weight and angle of internal friction of stone aggregates at 70% relative density are 14.51 kN/m^3 and 42° respectively. The particle size distribution curves for both clay and crushed stones are shown in Fig. 1

Table 1
Details of experimental programme.

Test description		Reinforcing material type	Strip spacing (mm)	Loading type		Tests
Type of piles	Reinforcement type			Pile alone	Entire area	
–	Clay bed	–	–	✓	✓	2
Floating	Unreinforced	–	–	✓	✓	2
End bearing			–	✓	✓	2
Floating	Vertical encased	Geotextile	–	✓	✓	2
End bearing			–	✓	✓	2
End bearing	Horizontal strips	Geogrid	25	✓	–	1
			50	✓	–	1
			70	✓	–	1
End bearing	Vertical encased and horizontal strips	Geogrid and geotextile	25	✓	✓	2
			50	✓	✓	2
			70	✓	✓	2
Total tests						19