Geotextiles and Geomembranes 28 (2010) 268–280

Contents lists available at ScienceDirect

Geotextiles and Geomembranes

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

Bearing capacity of reinforced foundation subjected to pull-out loading in 2D and 3D conditions

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ARTICLE INFO

Article history:
Received 27 May 2008
Received in revised form
23 January 2009
Accepted 15 July 2009
Available online 25 November 2009

Keywords:
Finite element analysis
Pile foundation
Reinforcement

ABSTRACT

Steel-framed structures like electricity transmission towers are subjected to great pull-out forces under strong wind conditions. This paper analyses how caisson foundations with reinforcement bars can increase the uplift bearing capacity of those structures. Model tests and numerical analyses in 2D and 3D are used to investigate how the bars' position and direction affect the behavior of the foundation under different load conditions. The test results show that reinforcements stemming diagonally downward from the bottom of the foundation are the most effective against uplift loading because they increase the structure's bearing capacity. However, this gain is less significant when inclined uplift forces are applied to the foundation. The higher the force inclination angle, the less efficient the design becomes. In that case, reinforcements that stem from the foundation's bottom are more effective than those stemming from the foundation's side. The numerical results accurately describe the experimental findings, since the simulations accounted appropriately for both the mechanical behaviors of the soil and the reinforcement as well as the frictional behavior between them. Furthermore, the results from the model tests and analyses carried out in 3D and 2D conditions are compatible.

1. Introduction

Foundations with reinforcements stemming from the side of the foundation diagonally downward or horizontally were developed and constructed to increase the uplift bearing capacity of electric transmission towers and other similar structures (Matsuo and Ueno, 1989; Tokyo Electric Power Company and Dai Nippon Construction, 1990). Nakai and Ueno (1996), Nakai et al. (1999, 2001) and Hinokio et al. (2007) investigated the mechanism of this type of foundation with reinforcements by means of 2D numerical simulations and model tests. The numerical and experimental results showed that the reinforcements stemming diagonally downward from the side of the foundation are the most effective when the foundation is uplifted vertically. However, reinforcements set up in that way were not effective against inclined uplift loading.

This study describes the behavior of 2D and 3D model tests of the foundations using stiff and flexible reinforcements under vertical and inclined uplift loading conditions. The main objective is to investigate the mechanism of reinforcement and to find out the most effective arrangement under different loading conditions. Attention is paid particularly to the direction and position of the reinforcements. The numerical analyses are carried out with FEMtij-2D and FEMtij-3D finite element software developed by the first author and collaborators at Nagoya Institute of Technology, Japan. In the finite element analyses, the subloading t_{ij} model (Nakai & Hinokio 2004) is used as an elastoplastic constitutive model. This model can describe typical stress deformation and strength characteristics of soils such as the influence of intermediate principal stress.

2. Description of model tests

Fig. 1 shows a schematic diagram and a photo of the apparatus used for the 2D model tests. The model of the ground was 100 cm wide and 50 cm high. It was composed of 5 cm long aluminum rods with diameters of 1.6 mm and 3.0 mm mixed with a weight ratio of 3:2. The unit weight of the mass was 20.4 kN/m^3. Fig. 2 presents the schematic diagram and a photo of the apparatus used for the 3D model tests. The 3D model of the ground was 100 cm wide, 80 cm long and 50 cm high. It was composed of alumina balls of different diameters, 2.0 mm and 3.0 mm, mixed with the ratio of 1:1 in weight. The unit weight of the mass was 21.5 kN/m^3.

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doi:10.1016/j.geotexmem.2009.09.013

The foundation piles were set up before building the model of the ground for both 2D and 3D conditions. These piles were 23 cm long and penetrated 18 cm into the ground. The pile used in the 2D model tests was rectangular and 6 cm wide (Fig. 3). The foundation used in the 3D model tests had the same dimensions but it was cylindrical.

Fig. 4a–c illustrates the arrangement of the reinforcements. Due to construction constraints in real cases, the length of reinforcement bars stemming from the sides of the foundation should be smaller than the caisson diameter. Therefore these lateral bars were 5 cm long for the foundation diameter of 6 cm in the model tests. However the reinforcements stemming from the bottom of the foundation can be longer. Three series of reinforcement patterns were investigated. The first series considered reinforcements stemming form a constant depth of 15 cm from the surface and inserted in three different directions: diagonally upward ($\beta = -30^{\circ}$), horizontal ($\beta = 0^{\circ}$) and diagonally downward ($\beta = 30^{\circ}$). The second series tested three installation depths for horizontal ($\beta = 0^{\circ}$) reinforcements: 15 cm, 12 cm and 6 cm from the ground surface. The third series analyzed the case where 10 cm long reinforcements stemmed vertically

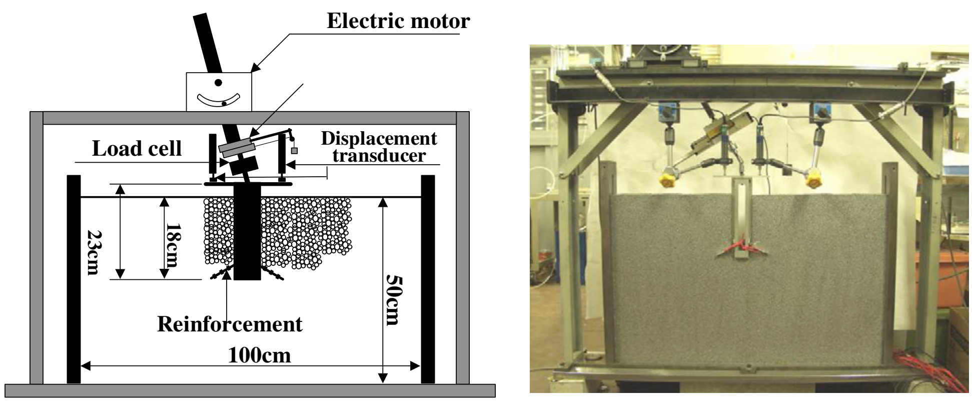

Fig. 1. Schematic diagram and picture of 2D model tests.

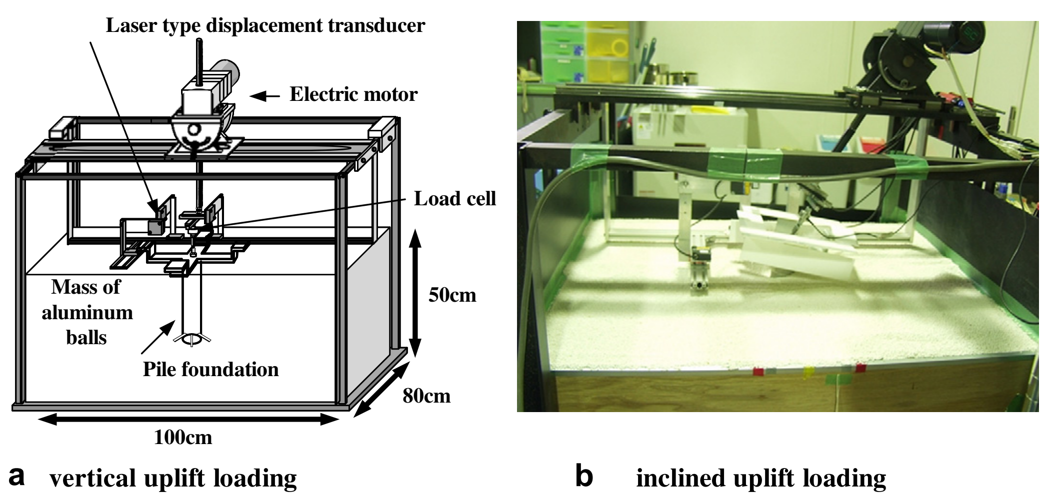

Fig. 2. Schematic diagram and picture of 3D model tests.

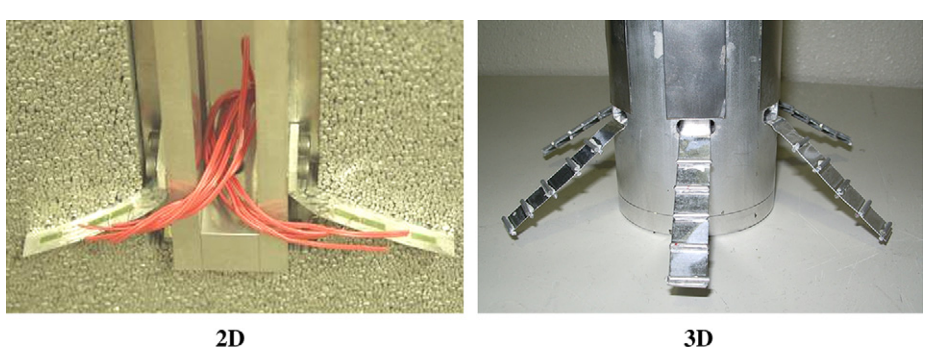

Fig. 3. Pictures of piles with reinforcement.