Soils and Foundations 2012;52(6):1102–1117

The Japanese Geotechnical Society

Soils and Foundations

www.sciencedirect.com
journal homepage: www.elsevier.com/locate/sandf

Rapid pile load tests in the geotechnical centrifuge

P. Hölscher[a,*], A.F. van Tol[b], N.Q. Huy[c]

[a]Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands
[b]Delft University of Technology/Deltares, P.O. Box 177, 2600 MH Delft, The Netherlands
[c]University of Civil Engineering, Department of Structural Mechanics, 55 Giai Phong Road, Hanoi, Vietnam

Received 29 August 2011; received in revised form 8 July 2012; accepted 14 October 2012
Available online 20 December 2012

Abstract

Centrifuge experiments were conducted to learn about the factors that affect mobilised resistance during rapid load testing of piles in sand. We studied the influence of pore water pressure during rapid load tests and its effect on the widely used unloading point method to derive static pile capacity. This paper describes the testing programme and the test set-up. We present typical measurement results from a total of 36 rapid and 12 static load tests, as well as the effects of the loading rate and excess pore pressures on pile resistance. The tests confirm that a rapid load test can overestimate static capacity due to pore water pressure when testing piles in medium to fine sands. The results of the pore pressure measurements show a combination of positive and negative excess pore pressure in the zone around the pile base, which can be explained by compression, volumetric behaviour during shearing and pore fluid flow around the pile.

Keywords: Piles; Sand; Bearing capacity; Centrifuge modelling; Pore pressure

1. Introduction

Rapid pile load test (RLT) methods such as the Statnamic test (Bermingham and Janes, 1989; Middendorp et al., 1992), the pseudo-static pile load tester (Schellingerhout and Revoort, 1996), or the spring hammer rapid load test method (Matsuzawa et al., 2008) are conside red to be efficient alternatives to static pile load testing (SLT). To improve the usefulness of the test, uncertainties regarding the assessment of the derived static capacity must be clarified. One such uncertainty is the effect of generated excess pore pressure. During the rapid load test, excess pore water pressure is generated in the soil close to the pile, even in sand (Hölscher, 1995; Maeda et al., 1998). It is unclear how this excess pore pressure affects the equivalent static stiffness and the ultimate bearing capacity of the pile.

The most common method for deriving equivalent static pile capacity from a rapid test is the unloading point method (UPM) (cf. Middendorp et al. (1992)). This method takes into account soil viscous damping and pile inertia, but not the effect of pore pressure. According to McVay et al. (2003), the rapid load test interpreted with the UPM overestimates the ultimate static capacity of piles in sand by an average of 10%. Analysis of more recent tests by Hölscher et al. (2008) confirmed the findings of McVay et al. (2003). Nevertheless, the UPM provides a good correlation with static load tests for piles in sand and gravel (Brown, 1994; McVay et al., 2003).

We studied the effect of excess pore pressure by performing a number of rapid load tests on piles in sand in a geotechnical centrifuge. Our aim was to determine

*Corresponding author. Tel.: +31 883357343.
E-mail address: Paul.Hoelscher@Deltares.nl (P. Hölscher).
Peer review under responsibility of The Japanese Geotechnical Society.

Production and hosting by Elsevier

0038-0806
http://dx.doi.org/10.1016/j.sandf.2012.11.024

whether the excess pore pressure is responsible for the 10% overestimate of static capacity referred to above. If indeed it is, and if the effect can be predicted, this opens up the possibility of the more accurate calculation of equivalent static pile capacity from an RLT.

Some centrifuge experiments described in the literature are relevant to the topic of non-static pile load testing in a centrifuge (Allard, 1990; De Nicola and Randolph, 1994; Bruno and Randolph, 1999). These tests focussed on the behaviour of piles or the surrounding sand during a dynamic pile load test, but none considered pore pressure response adequately. Allard (1990) performed the experiments in dry sand. De Nicola and Randolph (1994) and Bruno and Randolph (1999) used oil-saturated silica flour, to ''scale correctly the pore pressure generation and dissipation during the installation''. They focussed on pile driving and dynamic testing without measuring the excess pore pressure in the soil.

This paper focusses on the generation of excess pore pressure during RLT. Firstly, the tests elucidate the occurrence of excess pore water during a test and its influence on bearing capacity. Secondly, the tests provide information on the governing parameters. Finally, we present a practical implementation.

2. Scaling drainage conditions during rapid centrifuge tests

This section discusses how to deal with pore fluid in order to model pore pressure response correctly during a centrifuge rapid load test. The standard scaling rules for centrifuge modelling are well established in the literature (e.g. Altaee and Fellenius (1994), Sedran et al. (1998), Garnier et al. (2007)) and will not be repeated here.

Excess pore water pressure around a pile toe is the result of the dynamic equilibrium between the generation and dissipation of pore water pressure. To model the prototype pore water pressures in a centrifuge test correctly, generation, dissipation and wave propagation must be scaled properly. If the volumetric mass of sand and pore fluid are identical in the prototype and in the model, wave propagation will also be scaled correctly.

If one uses similar sand that is subject to stress levels similar to those in the prototype, it is assumed that the generation of pore water pressure will be correctly scaled (see e.g. Ovesen (1981)). In the remainder of this section, we focus on scaling the dissipation of pore water pressure.

If the scaling factor N is chosen for the length, the acceleration level in the centrifuge model will be N times higher than in the prototype. When the permeability k of a soil sample as defined by Darcy's law $k=Kg/v$ is considered (where K is the intrinsic permeability of the sand, g is the acceleration level, and v is the kinematic viscosity of the pore fluid), it can be seen that permeability in the centrifuge environment is increased N times. This implies that if the same sand and fluid (water) are used in the centrifuge as in the prototype, the pore pressure dissipation process (consolidation) in the centrifuge will be N^2 times faster. To compensate for this and to allow the same sand to be used, a fluid with a viscosity N times higher than water should be used, as proposed by Fuglsang and Ovesen (1987).

Huy et al. (2007) have stated that the effect of excess pore pressure in a rapid load test can be expressed by a dimensionless factor η, originally suggested by Hölscher and Barends (1992). This ''dynamic drainage factor'' is defined as

$$\eta = \frac{GT}{g\rho R^2}k = \frac{GT}{\rho R^2}\frac{K}{v}$$

where G is the shear modulus [N/m^2], T the duration of the loading [s], k the permeability of the soil [m/s], ρ the soil volumetric mass [kg/m^3] and R the pile radius [m]. To simulate the dissipation of pore pressure in a centrifuge test as realistically as possible, the starting point was to maintain an identical dynamic drainage factor in the model and prototype. If water is used in the centrifuge tests, the drainage factor will be N times smaller than in the prototype, since time is scaled with $1/N$ and the radius with $1/N^2$. If a fluid with N times higher viscosity is used, the drainage factor will be identical.

The dimensions of the test series were based on a scaling factor $N=40$ with respect to a fictitious full-scale field test (the ''prototype''). Using the prototype loading duration of a Statnamic test (100 ms) as a representative value, the loading duration of the model test should be 2.5 ms. However, the fastest loading duration of the available test facility was approximately 7.5 ms, three times slower than required. To compensate for this and to maintain the required dynamic drainage factor, it was necessary to increase the viscosity of the pore fluid threefold (i.e. $3\times40=120$ times higher than water).

A longer load duration may affect wave propagation in the soil. For the longest loading durations, it may no longer be possible to consider the load to be a rapid load. The relatively long duration of the tests means that they resemble an SLT more than in a field test. This issue is not important in terms of the purpose of the test.

The goal was to study the effects of pore pressure in a relevant drainage factor range and so it was decided to raise the viscosity of the fluid even more. The viscous fluid developed at Delft Geotechnics (Allard and Schenkeveld, 1994) was used in two centrifuge tests. This is a mixture of water and sodium carboxy methyl cellulose. The selected viscosity of the fluid was approximately 300 times higher than the viscosity of water, which is the maximum value for this application. The sand then has an apparent permeability of 2.5 (=300/120) lower than the correctly scaled value. Water was used as a pore fluid in one test to achieve nearly fully drained conditions. By varying the loading duration in each test, a difference of a factor of 5 in the drainage factor η was obtained.