Computers and Geotechnics 69 (2015) 485–495

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Research Paper

Predicting the axial capacity of piles in sand

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ARTICLE INFO

Article history:
Received 19 February 2015
Received in revised form 18 May 2015
Accepted 14 June 2015

Keywords:
Pile–soil interaction
Interface modelling
Design of experiment
Fractional factorial design
Central composite design
Bearing capacity

ABSTRACT

Currently, although several tools have been proposed for the numerical modelling of the pile–soil interface, there is not a well-established framework concerning the quantitative impact that different estimations of the mechanical properties of this setting have on the prediction of the bearing capacity of piles. With reference to the results of a finite element prediction of a centrifuge test on a pile in saturated sand, this paper presents a sensitivity analysis based on a design of experiment approach in an effort to solve this problem. The work proves the contribution of specific material parameters to the variation of the analyses results. Furthermore, the work highlights fundamental aspects to consider when modelling pile-related problems through the finite element method, looking at a comparable adherence to physical reality of the results.

1. Introduction

The geotechnical capacity of pile foundations with a predominant floating character is essentially dependent on the magnitude of the shaft friction, which is the force per unit area that defines the boundary between the foundation and the soil, i.e., the pile–soil interface. This contribution depends on strictly interconnected factors such as intrinsic soil properties, method of foundation installation, and foundation roughness [e.g., 1–6] that characterise the pile–soil interface, and crucially govern the pile equilibrium under any loading action. The suitable description of the features of the pile–soil interface is hence essential for capturing the pile–soil interaction and crucial for obtaining reliable results from predictions (e.g., finite element) of pile-related problems.

In the engineering practice it is often observed the fundamental issue of relying on a few material parameters from field investigations or experiments for the pile–soil interface modelling. Thus, empirical correlations are essential for characterising the mechanical properties of this setting. In this context, the following issues can arise: (i) the empirical formulations employed for this purpose are not proposed for a soil with the same properties as those considered in the analyses; (ii) the expressions do not refer to a foundation with similar features (i.e., roughness and stiffness) as those considered in the problem; (iii) the relations are not suitable to consider the effects of the construction method on the variation of the pile–soil interface parameters. All these aspects, together with fundamental choices related to the constitutive models and the modelling methods employed in the analyses to characterise the pile–soil interface, confronts engineers with the challenging problem of estimating the mechanical behaviour of the foundation with adherence to physical reality. Numerical sensitivity analyses devoted to assess the most sensible parameters for the variation of the analyses results become crucial for such purpose.

In recent years, different analyses have been performed to outline some of the pile–soil interface parameters that play an important role in the variation of the results of finite element predictions devoted to capture the axial capacity of piles [e.g., 7,8]. However, a well-established framework concerning the quantitative impact of different estimations of the mechanical properties of this setting on the considered problem is still missing. This lack is due to the fact that, to the authors' knowledge, rigorous methods for analysing any subject denoted by multiple input factors and determining their effect on a desired output through manipulation are very rare in the geotechnical engineering field, if not unavailable. This fact confronts engineers with the need to perform numerical sensitivity analyses that may require noteworthy employments of resources and time, eventually preventing the evaluation of the most sensible parameters for the variation of the analyses results.

Looking at this challenge, this work focuses on a systematic analysis of the issues that engineers may encounter when predicting the axial capacity of piles and proposes an approach that may

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http://dx.doi.org/10.1016/j.compgeo.2015.06.013

be exploited for the best quantitative characterisation of any engineering problem with the lowest development of analyses. In particular, this study investigates through a design of experiment approach the impact of different estimations of the mechanical properties of the pile–soil interface on the numerical prediction of the bearing capacity of semi-floating piles in sand subjected to axial mechanical loading. The analyses exploit the results of a "class B" [9] finite element prediction (simulation of an event that is being performed without the availability of the associated results) [10] of a centrifuge test [11] aimed to estimate the axial capacity of a single semi-floating pile in saturated Toyoura sand. The corroboration of the numerical approach with experimental data allows assessing the adherence to physical reality of the considered method. The finite element prediction, along with the method exploited to model the pile–soil interface, is considered the base-case for the investigation. A fractional factorial design (i.e., first-order degree model) and a central composite design (i.e., second-order degree model) are applied to outline the impact of alternative estimations of the mechanical properties of the pile–soil interface on the variation of the base-case prediction results. The goal of the study is to propose quantitative data to capture the complex pile–soil interaction in a range of problems characterised by similar features to those considered in this study and estimate the bearing capacity of semi-floating piles with suitable adherence to physical reality.

2. The modelled problem

The base-case numerical prediction considered in this study was performed in the context of a collaborative research project between the Swiss Federal Institute of Technology in Lausanne (EPFL) and the Hong Kong University of Science and Technology (HKUST). The aim of this project was to investigate the response of energy piles in saturated sand subjected to thermo-mechanical loads through the so-called "modelling of prototype-scale scenarios" technique, i.e., the application of finite element analyses and centrifuge tests for analysing real world problems. Finite element predictions were performed at the EPFL [10], whereas centrifuge tests were performed at the Geotechnical Centrifuge Facility of the HKUST [11]. One of these tests involved the mechanical loading until failure of a canonical pile foundation surrounded by a saturated deposit of Toyoura sand. The features of the numerical prediction of this test are summarised in the following for the purpose of the present study (base-case) and compared for reference to the centrifuge test results.

2.1. Geometry

An axisymmetric finite element model was built to reproduce a single prototype-scale pile surrounded by a saturated deposit of Toyoura sand (cf. Fig. 1) [10]. The prototype-scale pile had a diameter $D = 0.88$ m and length $L = 19.6$ m. This finite element model reproduced in real-scale the model-scale aluminium pile that was tested in the centrifuge at 40-g (where g is the Earth's gravitational acceleration) by Ng et al. [11]. The model-scale pile had a diameter $D = 22$ mm and length $L = 490$ mm.

A fine mesh of 920 quadrilateral, 8-noded elements and 2 linear, 2-noded elements gave a total of 2887 nodes to describe the finite element model (cf. Fig. 1). The fine mesh prevented mesh-dependence issues and subsequent ill-conditioning of the results that can be caused by a coarse mesh that is characterised by bad aspect ratio elements [12]. The mechanical load was applied to the head of the foundation by the 2 linear elements (constant normal load boundary condition). The foundation was described by 40 of the 920 exploited quadrilateral elements. The pile–soil interface was modelled using a layer of standard aspect ratio finite elements (elements characterised by a fraction between their height and thickness greater than 3 but less than 10 [12]), i.e., 20 quadrilateral elements with an aspect ratio of 9.8. The soil was characterised by the remaining 860 quadrilateral elements. The main advantages related to the use of standard aspect ratio elements for the modelling of the pile–soil interface were the lack of a need to perform integrations of special elements in the finite element model and the lower computational efforts required to run the numerical simulations.

The dimensions of the finite element model were ten times the pile radius in the horizontal direction and three times the pile length in the vertical direction.

2.2. Mathematical formulation

The finite element software used to run the numerical analyses was Lagamine [13,14]. Coupled hydro-mechanical numerical analyses were performed to model the considered problem. The foundation, the soil and the pile–soil interface were considered to be porous materials. The coupled mathematical formulation used in

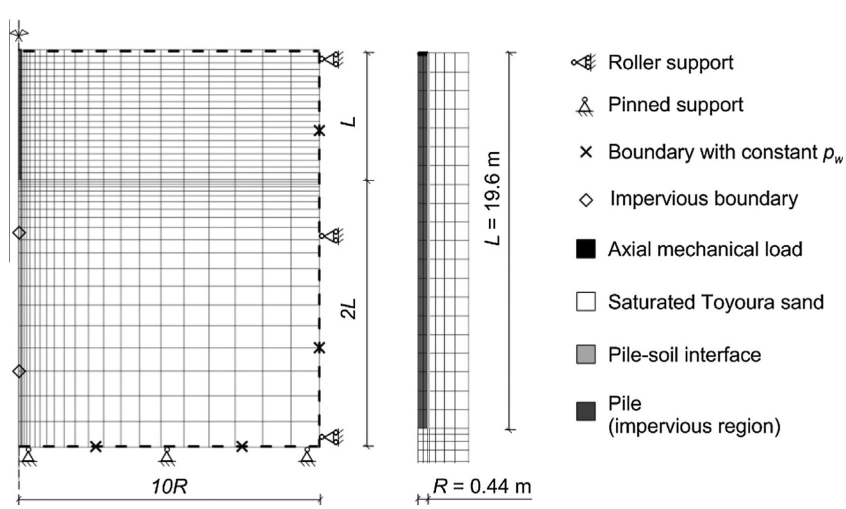

Fig. 1. Finite element mesh used for the numerical simulations.