Computers and Geotechnics 63 (2015) 73–82

Contents lists available at ScienceDirect

Computers and Geotechnics

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

Non-linear analysis of vertically loaded piled rafts

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A R T I C L E I N F O

Article history:
Received 20 March 2014
Received in revised form 23 July 2014
Accepted 25 August 2014
Available online 19 September 2014

Keywords:
CPRF
Piled raft
Pile group
Non-linear

A B S T R A C T

While the availability of 3D FEM or FDM analyses has greatly contributed to the increasing use of piled rafts for high rise structures, there is a need in industry for practical analysis methods which would also allow the adoption of piled rafts for more ordinary structures. For this purpose, a 3D boundary element solution is proposed for computing the non-linear response of piled rafts to vertical loads. The validity of the analysis is demonstrated through comparison with alternative numerical solutions and field measurements. Examples are given to demonstrate the basic importance of considering soil nonlinearity effects in design, thereby leading to more realistic predictions of the raft and pile response. The key feature of the proposed approach lies in its computational efficiency which makes the analysis economically viable not only for the design of piled rafts supporting high rise buildings (generally based on complex and expensive 3D FEM or FDM analyses) but also for that of bridges, viaducts and normal buildings.

1. Introduction

In conventional foundation design, it is assumed that the applied load is carried either by the raft or by the piles, considering the safety factors in each case. In recent years, an increasing number of structures (especially tall buildings) have been founded on Combined Pile–Raft Foundations (CPRFs), an attractive foundation system which allows the load to be shared between the raft and the piles, thereby offering a more economical solution. In the design of piled rafts, a sufficient safety against geotechnical failure of the *overall* pile–raft system has to be achieved, while the piles may potentially be used up to their ultimate geotechnical capacity. Contrary to traditional pile foundation design, no proof for the ultimate capacity of each individual pile is necessary [14]. Given the high load level at which the piles operate, consideration of soil nonlinearity effects is essential, and ignoring this aspect can lead to inaccurate predictions of the deformations and structural actions within the system.

Due to the 3D nature of the problem and the complexity of soil-structure interaction effects, calculation procedures for piled rafts are based on numerical analyses, ranging from simplified Winkler approaches to rigorous 3D finite element (FEM) or finite difference (FDM) solutions using available packages. Winkler approaches employ a "plate on springs" model in which the raft is represented by a plate and the piles as springs (e.g. [7,25,15,19,22,13]). Although such approaches are attractive in their flexibility (e.g. enabling non-linear soil response to be incorporated easily), they suffer from some restrictions mainly related to their semi-empirical nature and fundamental limitations (e.g. disregard of soil continuity).

A more rational approach is offered by soil continuum-based solutions such those based on the boundary element method (BEM) in which both the raft and the piles within the system are discretized using elastic theory (e.g. [5,17]). Several hybrid approaches have also been developed, in which the raft is modelled via FEM and the piles are modelled either via BEM [11] or using the finite layer method [35]. All these analyses are however restricted to linear elastic soil behaviour.

The above restriction may be removed by using 3D FEM and FDM solutions (e.g. Plaxis 3D and FLAC-3D) which allow complex geometries and soil behaviour to be modelled, while retaining continuity within the soil mass. However, such analyses are burdened by the high computational cost and specialist expertise needed for their execution, particularly when non-linear soil behaviour is to be considered. Major difficulties are related to the high mesh dependency and the uncertainty in assigning mechanical properties to the pile–soil interface elements (e.g. [18]). This aspect restricts their practical application in routine design, where multiple load cases need to be examined and where the pile number, properties, and location may have to be altered several times in order to obtain an optimised solution. This is particularly true in the case of "ordinary" piled rafts (e.g. bridges, viaducts, wind turbines, normal buildings) where the cost and complexity of conducting 3D FEM or FDM analyses can rarely be justified.

In an attempt to provide a practical tool for the designer, the paper describes an efficient analysis method for computing the

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http://dx.doi.org/10.1016/j.compgeo.2014.08.011
0266-352X/

response of piled rafts. The originality of the approach lies in its capability to provide a non-linear BEM solution of the soil continuum, while retaining a computationally efficient code, thereby removing some of the limitations of current design methods. The validity of the proposed analysis is assessed through a comparison with alternative numerical solutions and a published case history. Examples are given to highlight the significance of considering soil nonlinearity effects, thereby leading to more realistic predictions of the raft and pile response.

2. Analysis method

The safe and economic design of piled rafts requires non-linear methods of analysis which have the capacity of simulating all relevant interactions between the foundation elements and the subsoil, specifically (1) pile–soil-interaction (i.e. single pile response including shaft-base interaction), (2) pile–pile-interaction (i.e. group effects), (3) raft–soil-interaction, and (4) pile–raft interaction, as illustrated in Fig. 1a [14].

The proposed method is an extension to the raft analysis of the non-linear BEM formulation employed in the pile-group program PGROUPN [2] and widely used in pile design through the software Repute [3]. The main feature of the approach lies in its ability to perform a complete 3D BEM analysis of the soil continuum (i.e. the simultaneous influence of all the pile and raft elements is considered), while incurring negligible computational costs. Indeed, compared to 3D FEM or FDM analyses, BEM provides a complete problem solution in terms of boundary values only, specifically at the raft–pile–soil interface. This leads to a drastic reduction in unknowns to be solved, thereby resulting in substantial savings in computing time and data preparation effort. This feature is particularly significant for three-dimensional problems and makes the analysis economically viable not only for the design of piled rafts supporting high rise buildings (generally based on complex and expensive 3D FEM or FDM analyses) but also for that of bridges, viaducts and ordinary buildings.

The main capabilities of the PGROUPN program, including the proposed extension to the raft analysis, are summarised below:

- based on 3D complete BEM solution of the soil continuum;
- models all relevant interactions (i.e. pile–soil, pile–pile, raft–soil, and pile–raft);
- piles in any configuration and having different characteristics within the same group (e.g. stiffness, length, rake, shaft and base diameter);
- piles connected by fully rigid ground-contacting raft;
- non-homogeneous and layered soil profiles;
- linear or non-linear continuum-based soil model;
- general 3D loading conditions, including any combination of vertical, horizontal, moment, and torsional loading;
- output includes the distribution of displacements, stress, forces, and moments along the piles, plus the normal stress, displacements, and rotations of the pile cap.

2.1. PGROUPN boundary element formulation

A detailed description of the theoretical formulation adopted in PGROUPN for the case of pile groups has been presented elsewhere [1,2]. The boundary element modelling of the soil-structure interaction for the piles and for the raft is similar and, hence, only a brief outline of the raft analysis is given below. Similarly to the discretization of the pile–soil interface into a number of cylindrical elements, the approach is now extended to the raft analysis (including its reciprocal interaction with the piles) by discretizing the raft–soil interface into a number of rectangular elements (Fig. 1b). The behaviour of each element is considered at a node (located at the centre of the element), each element being acted upon by uniform normal stress. Thus, only the bearing contribution of the raft underside is considered (i.e. the raft–soil interface is assumed to be smooth). It should be emphasised that the analysis takes into account the simultaneous influence of all the raft and pile elements within the foundation system, i.e. a "complete" solution of the soil continuum is adopted. All four of the above interactions (i.e. pile–soil, pile–pile, raft–soil, and pile–raft) are therefore evaluated as a matter of course, thereby overcoming the approximations of the traditional interaction factor approach and the fundamental limitations of Winkler models (based on empirical multipliers to account for group action). In addition, by retaining soil continuity, the input soil parameters required by PGROUPN have a clear physical meaning (e.g. the soil Young's modulus and strength properties) and can be measured directly in a soil investigation. This aspect represents a significant advantage over Winkler approaches which disregard soil continuity and, therefore, have to rely on empirical parameters (e.g. the modulus of subgrade reaction).

The boundary element method involves the integration of an appropriate elementary singular solution for the soil medium over the surface of the problem domain, i.e. the raft–soil interface. Under the assumption of purely linear elastic soil behaviour, the well-established solution of Mindlin [20] is adopted to correlate soil stress (t_s) and displacements (u_s) at the raft–soil interface:

$$u_s = [G_s]t_s \tag{1}$$

where $[G_s]$ is the soil flexibility matrix obtained from Mindlin's solution. The singular part of the $[G_s]$ matrix is calculated via analytical integration of the Mindlin functions over each

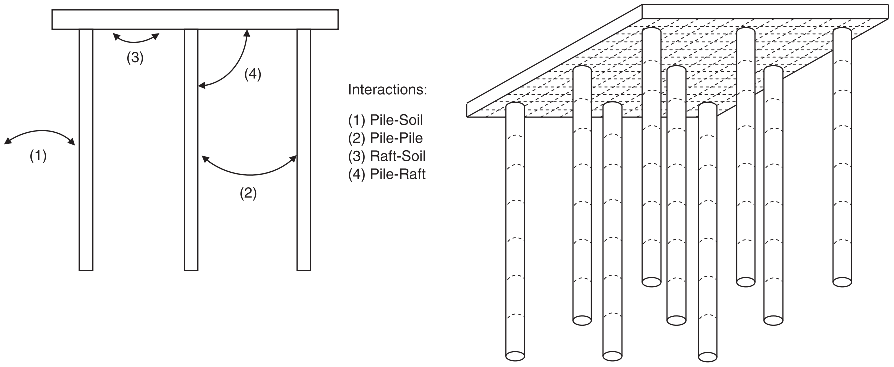

Fig. 1. (a) Soil-structure interactions in piled raft and (b) PGROUPN boundary element mesh.