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Non-linear soil–structure interaction in disconnected piled raft foundations

F. Tradigo [a,*], F. Pisanò [a], C. di Prisco [a], A. Mussi [b]

[a] Department of Civil and Environmental Engineering, Politecnico di Milano, Piazza Leonardo da Vinci, 32, 20133, Milan, Italy
[b] ARUP, Milan, Italy

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ABSTRACT

Disconnected piled raft foundations are characterised by no structural connection between the upper raft and the underlying piles, mostly playing the role of settlement-reducers. The resulting raft–pile gap is usually filled with a granular interlayer, through which the loads from the superstructure are transferred to the piles.

In this paper, the complex interaction mechanisms involving the foundational components (raft, piles and soil) are numerically investigated by means of 3D finite elements analyses, accounting for soil non-linearity. The main features of the soil–structure interaction mechanisms under purely vertical external loads are explored over a realistic range of raft–soil gaps for different pile configurations, in which the number of piles – i.e. their spacing – is varied. Special attention is also devoted to the structural response of the piles in terms of axial and bending internal stress resultants. In particular, while disconnection beneficially affects the structural pile response, increasing the raft–pile gap tends to reduce the overall settlement/stiffness efficiencies.

The numerical results being presented are in substantial agreement with the outcomes from literature small-scale experiments and suggest a number of relevant theoretical inferences.

1. Introduction

In the presence of certain structural/geotechnical conditions, raft and pile foundations can be fruitfully combined with the two-fold goal of (i) increasing the global bearing capacity and (ii) reducing the settlements induced by service loads – as was first proposed by Burland et al. [1]. In the latter respect, *piled rafts* (PRs) and *disconnected piled rafts* (DPRs) are to be distinguished, depending on whether the piles are structurally connected or not to the raft.

As mentioned by Poulos [2], PRs embody a possible realisation of the so-called *creep piling* design approach defined by Randolph [3], in which piles work under quite high loads. The adoption of PR foundations is also associated with interesting economical and environmental benefits: as reported by Huang et al. [4], this design approach has been widely applied in China, to the extent that designing settlement-reducing piles for tall buildings is currently mandatory in Shanghai.

In recent years, the use of DPR foundations has been gaining increasing popularity [5]. In this alternative setup for settlement-reducing piles, there is no pile–raft structural connection and the pile/raft gap is filled with a layer of compacted granular material. This latter avoids the loads coming from the superstructure to be directly applied on the piles, so that the design of DPRs – at variance with PRs – is no longer driven by severe structural requirements. From a design perspective, the adoption of DPRs allows for lower safety factors for the piles.

The present work focuses on deep foundations for tall buildings on sandy grounds, where the serviceability requirements related to settlement reduction are the most demanding [6]. Tall buildings usually rest on so-called *large* piled rafts, where:

– the "unpiled" bearing capacity is proportional to the raft width and thus rather large. Conversely, high (or even unacceptable) settlements are quite likely to take place;
– the L/B ratio between the pile length and the raft width is usually low ($L/B \leq 1$).

The mechanical response of these foundational systems results from complex soil–structure interaction mechanisms, whose analysis and interpretation are still under discussion within the technical community. Improving the insight into such interaction phenomena is preliminary to optimal design and, therefore, to an effective use of piles in engineering practice.

* Corresponding author.
E-mail address: fabio.tradigo@polimi.it (F. Tradigo).

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Recently, several methods for both bearing capacity and settlement analyses on PRs have been developed in the form of (i) empirical formulas, (ii) analytical relationships derived from simplified theories and (iii) numerical computations based e.g. on the finite element (FE) method. As commented by Poulos [2], the intrinsic complexity of the raft–soil–pile mechanical interaction renders standard design approaches for PRs – i.e. analytical or approximate computer-based – unlikely to produce rigorous results. Conversely, resorting to three-dimensional FE analyses seems to be the most reliable option, since complex geometries and material non-linearities can be taken into account [7,8]. The suitability of FE analyses is even more evident in the case of DPRs, where very complex raft–soil, pile–soil, pile–pile interactions are expected to take place.

In the context of numerical approaches, several authors have been performing FE parametric analyses on DPRs to investigate the influence of different geometrical/mechanical factors, such as the cushion stiffness, the gap and the raft thickness, the overall piling configuration. For instance, Liang et al. [9] studied in the elastic regime how the cushion stiffness and the gap thickness affect load redistribution over short (placed along the raft perimeter) and long (underneath the raft center) piles; this study suggests how to optimise the piling configuration in order to evenly distribute the loads and mitigate stress concentration on the longer piles. Eslami and Malekshah [10] performed elasto-plastic analyses to show the reduction in the average settlement coming from either decreasing the gap thickness or increasing the stiffness of the filling material; the authors found the differential settlements to decrease as long as piles are concentrated under the raft centre. Also, the maximum axial stress along the piles resulted at different depths depending on the thickness and the stiffness of the pile–raft gap.

Most of the above numerical findings are qualitatively confirmed by experimental data from small-scale tests, which have been performed under either real gravity [11–13] or centrifuge [14,15] conditions. While the importance of numerical–experimental comparisons is self-evident, performing experiments of the aforementioned kind is particularly expensive and time-demanding. This further supports the need for reliable and well-established numerical modelling of DPR foundations.

Following from the above premises, the contents of this paper are arranged as it follows. After a preliminary summary of the main experimental results in literature concerning DPRs, the most relevant features of the FE model here employed for numerical analyses are detailed. Then, a set of numerical results are presented to highlight some relevant features of the soil–structure interaction mechanisms in DPRs, as well as of the pile structural response. The last section is devoted to parametrically explore how pile spacing and pile–raft disconnection influence the settlement and the structural performance of DPR systems.

2. Inferences from experimental results

In recent years, the behaviour of DPRs has been investigated by performing both 1 g [11] and centrifuge [14,15] experiments on small-scale models. At a first glance, substantial – yet qualitative – agreement was found between the experimental measurements on PRs and DPRs and the outcomes from (simplified) numerical analyses [5,9,16,4,10]. In the light of the connection to the following numerical results, the main conclusions experimentally drawn by Cao et al. [11] Fioravante and Giretti [14], Fioravante [15] are hereafter recalled.

Cao et al. [11] evaluated the effectiveness of disconnected piles as settlement reducers by subjecting small-scale DPRs to vertical loading. In particular, the raft stiffness, the length, the spatial setup and the number of piles were varied to assess their influence on the average and differential settlements; also, strain gauge measurements along the structural members were used to obtain the bending moments and axial forces within the raft and the piles, respectively. The authors underlined the link between the skin friction distribution along the pile shaft and the location of the

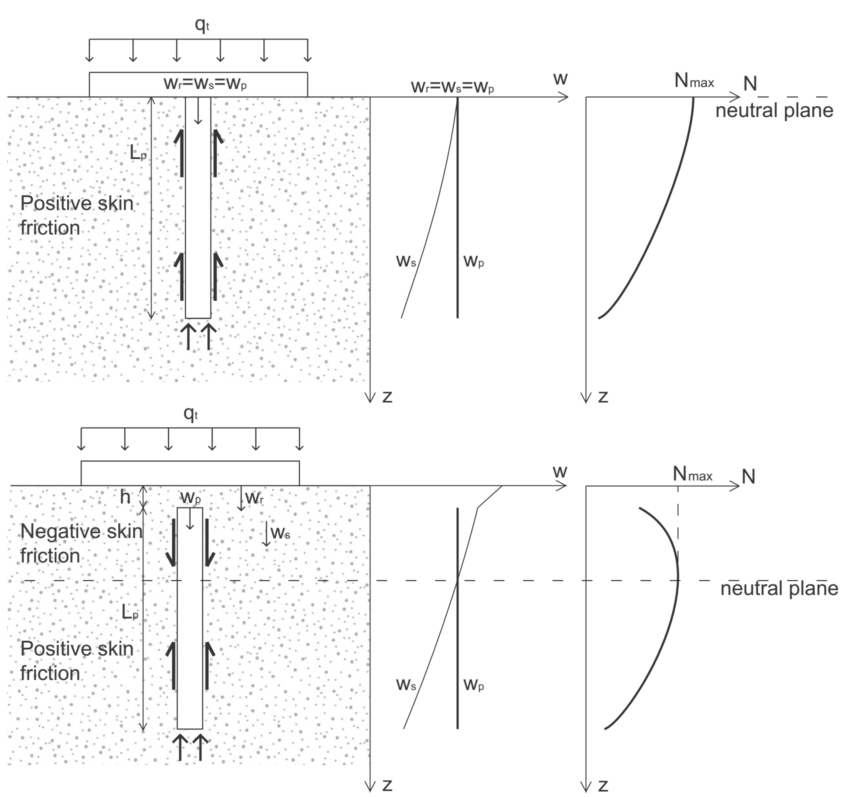

Fig. 1. PR and DPR settlements along depth.