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Optimizing foundation performance: the impact of raft on piled raft foundation in sand

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Conventional piled foundation designs tend to be overly conservative since the beneficial role of the raft is often neglected by assuming the piles to be the only part of the structure interacting with the soil. The contribution of the raft to the global response of the foundation is particularly important in the case of "large" piled rafts, where the pile length is comparable to the raft width. This configuration, although not theoretically optimal, is common for existing foundations of bridges and high-rise buildings. Although the beneficial effect of raft–pile–soil interaction on both bearing capacity and stiffness is generally acknowledged, simple and reliable approaches recognized by design codes are not yet available. Aiming at providing simple tools for designing large piled rafts under static and dynamic/cyclic loads, in this paper a numerical study is presented, with preliminary finite element analyses performed to examine the mechanical behaviour of a "large" piled raft under vertical centred loads and positioned on a dry sand layer. This paper presents the findings of this study, comparing the performance of the piled raft to the corresponding pile group and unpiled raft, and highlights the importance of considering the presence of rafts in the design of piled foundations.

KEYWORDS: axial loading; finite element analysis; foundation design; piled raft; soil-structure interaction; UN SDG 9: Industry; innovation and infrastructure; UN SDG 12: Responsible consumption and production

INTRODUCTION

The foundations of many early 20th-century European infrastructure have now reached the end of their intended design life, necessitating a reassessment of their safety under current conditions. Conventional piled foundation design tends to be overly conservative, often leading to the conclusion that these foundations no longer meet all the design criteria. Retrofitting foundations is a costly and technically challenging process that demands significant resources and raw materials. Therefore, retrofitting should be undertaken only when absolutely necessary.

One of the most significant factors contributing to this over-conservatism in design is neglecting the contribution of the structural element (the raft) connecting the head of the piles and in contact with the soil to the foundation response. The contribution of the raft to the global response of the foundation system is of particular importance in the case of "large" piled raft (Viggiani *et al.*, 2014), in which the length of the piles is comparable to the width of the raft. Although from a theoretical perspective this configuration is not optimal, it is a very common solution in case of existing foundations characterized by large width such as the ones of bridges and high-rise buildings (see, for instance, Hooper, 1979; Sommer *et al.*, 1991; Van Impe & De Clerq, 1995; Katzenbach *et al.*, 2000; Mandolini *et al.*, 2005; Katzenbach & Choudhury, 2013; Tradigo *et al.*, 2017).

The beneficial effect of raft–pile–soil interaction on both bearing capacity and stiffness is generally acknowledged and has been experimentally (Horikoshi & Randolph, 1996; Lee and Chung, 2005; Nguyen *et al.*, 2013; Sawada and Takemura, 2014) and numerically (Reul & Randolph, 2003; de Sanctis & Mandolini, 2006; Deb & Pal, 2019; Han *et al.*, 2019; Chanda *et al.*, 2020; Psychari & Anastasopoulos, 2022; Sakellariadis & Anastasopoulos, 2022; Corigliano *et al.*, 2023a, 2023b) demonstrated. While the majority of research on piled rafts has focused on optimizing new foundations, concluding by recommending "small" rafts with long piles (e.g. Hanisch *et al.*, 2002; Viggiani *et al.*, 2014; Psychari & Anastasopoulos, 2022; Sakellariadis & Anastasopoulos, 2022), this research aims at valuing existing foundations, to leverage the infrastructure heritage for the sake of the sustainability. Specifically, the focus is set on the performance of large piled rafts where the pile length is comparable to the raft width, a configuration often considered suboptimal but commonly encountered in older infrastructures, especially bridges and very tall building foundations. By enhancing the understanding of raft contributions in these existing configurations, our study aims to extend the service life of foundations that are already built, thereby reducing the environmental impact associated with new constructions. Also design codes recognize the beneficial effect of the raft, however do not provide guidelines on how to account for this effect.

The final goal of the research carried out by the authors is to provide simple tools that can be used in the design of large piled rafts (PR) under a general combination (inclined and eccentric) of both static and dynamic/cyclic loads. To this aim, an experimental/numerical study is being conducted. As a preliminary step, the authors performed a finite element (FE) numerical study to design a series of 100 g centrifuge tests that will be performed considering a piled raft on a dry sand layer. The main goal of the FE simulations was to assess the feasibility of a series of experimental tests to be performed in the facility of the Technische Universiteit Delft. In addition, the FE simulation results highlight interesting aspects on the performance of a specific PR under vertical centred loads compared to the corresponding pile group (PG, i.e. a PR in which the soil–raft interaction is neglected) and unpiled raft (UR), and

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to highlight the importance of considering the presence of rafts in the design of piled foundations. In this paper, only the results of these FE simulations will be discussed.

FE MODEL

The mechanical response of a PR, a PG and a UR was studied by performing 3D FE analysis using PLAXIS 3D. In the PR and PG cases, the foundation consists of an 8·8 m × 4 m × 1·5 m raft (Fig. 1) supported by eight 8 m long piles with a diameter of 0·8 m. The chosen geometry, inspired by the case study of Corigliano *et al.* (2023a, 2023b), is the one that will be used in the centrifuge tests that are part of the wider research programme. The bored (non-displacement) piles are characterized by a length/diameter ratio equal to 10, but the pile length/foundation width ratio is equal to 0·9 ("large raft"). In the PG analysis, to prevent the interaction between the raft and the soil, a gap between the raft and the ground surface is present. In the UR case, the dimensions of the foundation are the same, but piles are not present. The domain is subdivided into 49,000 10-nodes tetrahedral finite elements (Fig. 1). On the vertical sides of the domain, normal displacements are imposed to be nil. On the base of the domain, all displacements are prevented.

The soil behaviour was modelled using the hardening soil constitutive model (Schanz *et al.*, 1999), whose parameters (Table 1) were calibrated based on what proposed in Brinkgreve *et al.* (2010) and E_{50}^{ref} was slightly reduced from 18 to 15 MPa to better match the results of a centrifuge test performed on a PR and validated on the experimental results of the corresponding PG and UR [Fig. 2(a) data from Marveggio *et al.* (2024)]. The unit weight is set to 15 kN/m^3.

The raft, the pier and the piles are assumed to be elastic. The properties are those of concrete (Young's modulus, Poisson's ratio and unit weight are equal to 30 GPa, 0·2 and 25 kN/m^3, respectively). Frictional interface elements were used between both soil-raft and soil-piles. The interface stiffness is set to be ten times the soil elastic oedometric one. The interface friction angle is assumed to be equal to two-third of the soil friction one (Fleming *et al.*, 2008). The results of a parametric study performed by the authors showed that the chosen interface properties allowed to accurately reproduce the system response. The results are here omitted for the sake of brevity.

According to Fleming *et al.* (2008) and Salgado (2008), when non-displacement piles are carefully installed, the state of stress is close to the initial geostatic conditions. Therefore, the stresses were initialized by following a K_0 procedure (K_0 is the at-rest lateral earth pressure coefficient).

Table 1. Parameters for hardening soil

Parameter	Value	Unit
E_{50}^{ref}	15	[MPa]←
E_{oed}^{ref}	15	[MPa]←
E_{ur}^{ref}	45	[MPa]←
v_{ur}	0·2	[←]←
m	0·65	[←]←
p_{ref}	100	[kPa]←
ϕ'	32	[°]←
ψ	2	[°]←

Subsequently, a vertical displacement is imposed in the central area of Fig. 1, representing a 1 m × 1 m column. The imposed final vertical displacement is equal to 100% of the pile diameter (approximately 9% of raft width).

RESULTS AND DISCUSSION

Figure 2(a) presents the load–displacement curves for the three cases. When compared to both PG (red line) and UR (blue line), the PR (black line) performs better, exhibiting significantly larger stiffness. This is completely different to what observed by Sakellariadis & Anastasopoulos (2022), who considered "small" rafts and both experimentally and numerically showed that the raft presence does not affect the load settlements curve. This implies that the beneficial raft-pile coupling effect is only relevant for "large" raft, as the one considered in this paper. For displacements lower than 50% of pile diameter, the stiffness of UR and PG are comparable, with UR exhibiting a slightly lower stiffness. For larger displacements, the UR reaches failure (i.e. its stiffness becomes zero, dashed blue line), whereas both PG and PR do not. In these two cases, "failure" must be defined as a maximum allowable displacement. The choice of this value, however, depends on the structure built on the foundation and is not addressed in this paper.

In a simplified way, as proposed by Randolph (1983) for linear elastic soils, piles and raft in a PR behaves like an in-parallel system. To verify the accuracy of this assumption in case of non-linear soil behaviour, the sum of PG and UR load–displacement curve is plotted in Fig. 2(a) (purple dashed line). Up to a displacement lower than 50% of pile diameter, the purple dashed line is similar to the PR one. For larger displacement values, the purple dashed curve is lower than the black one, implying that the raft–pile–soil interaction is beneficial for the system.

To better highlight this, Fig. 2(b) and 2(c) shows the contribution of piles (sum of axial forces at the pile head)

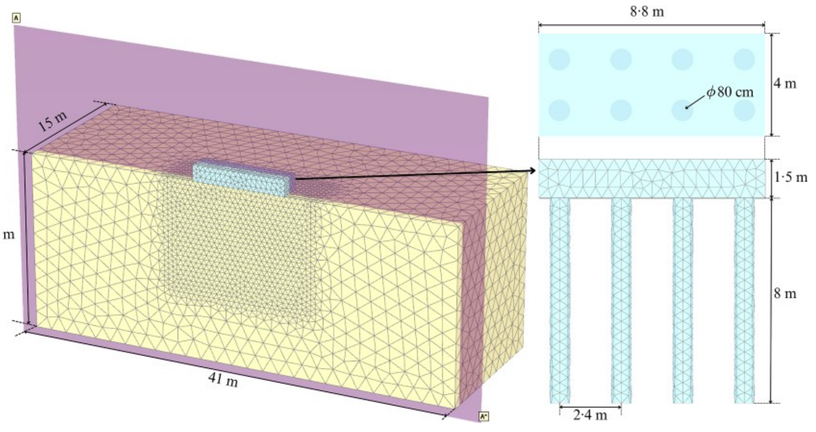
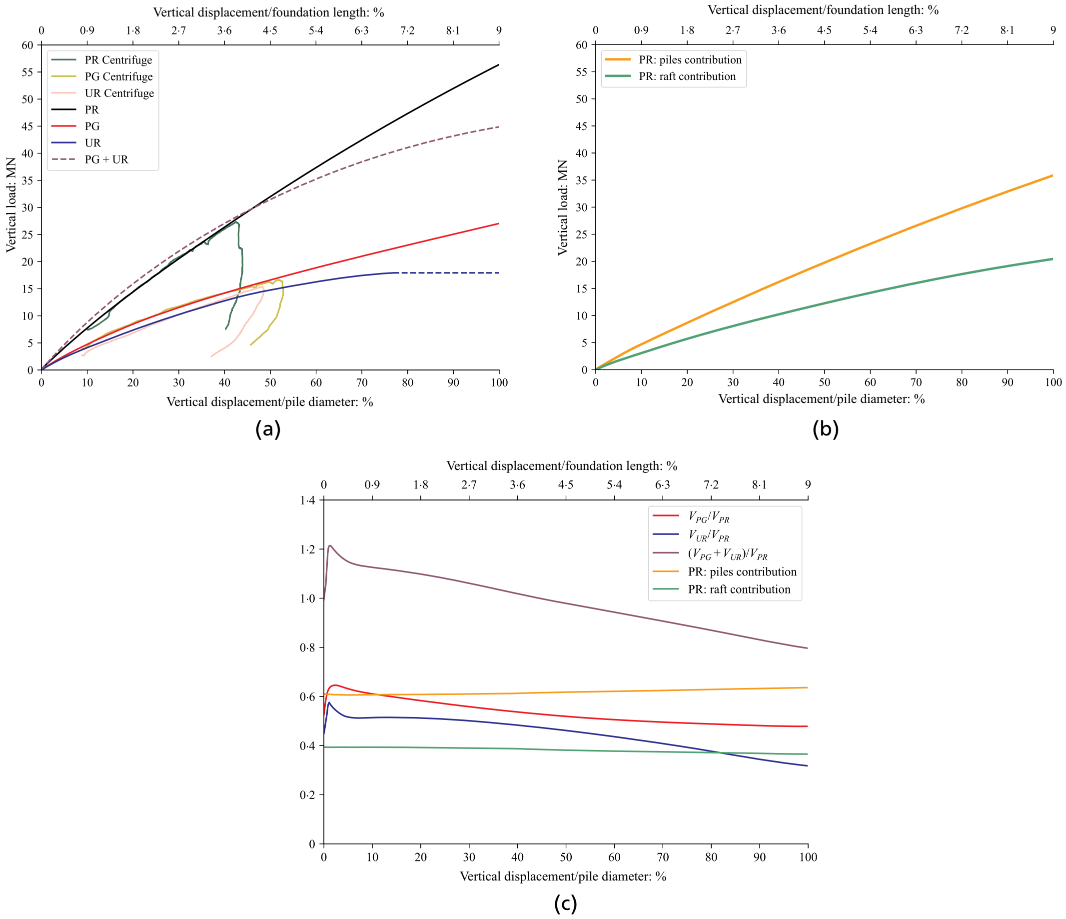


Fig. 1. Foundation geometry and finite element mesh



(a) (b) (c)

Fig. 2. a) Axial load–displacement curves for different foundation types (centrifuge data from Marveggio *et al.*, 2024), b) piles and raft contributions and c) vertical load contribution percentages

and of the raft for the PR case as a function of vertical displacement [in Fig. 2(b) as forces, whereas in Fig. 2(c) as a percentage of the applied load]. The raft contribution to the total load capacity is almost 40% and gently decreasing with displacement. This range aligns with the optimal range of 30%–50% for the raft contribution suggested by Hanisch *et al.* (2002) for technical and economic efficiency.

To further highlight the difference of the PR with respect to the ideal in-parallel system composed by UR and PG, Fig. 2(c) shows the vertical loads of UR (V_{UR}), PG (V_{PG}) and UR + PG, divided by the corresponding value of PR (V_{PR}). For low displacement values, the in-parallel system overestimates the PR performance (up to +20%), whereas for larger values it underestimates the PR performance (up to −20%). Comparing the PG curve with the corresponding contribution of piles in PR clearly shows the effect of the raft in improving the mechanical performance of the piles belonging to the PR.

The improvement of raft and piles response with respect to the UR and PG cases can be attributed to local interaction mechanisms taking place between the raft and piles, even though in all the cases, as suggested by the load displacement curve, the state is far from ultimate conditions. To highlight this, the vertical displacement and deviatoric strain contours are plotted in Fig. 3, which helps in better highlighting this mechanism than the almost linear load displacement curves. At a settlement of 20% of pile diameter, the PR [Fig. 3(c)] shows a displacement/strain pattern similar to the combined pattern of the pile group and raft [Fig. 3(a) + 3(b)]. However, the contours already suggest a pile-foundation coupling in case of PR: strains do not only develop in the proximity of the external pile [PG, Fig. 3(a)], but involve a larger domain subdomain [in Fig. 3(c), $\varepsilon_{dev} > 1\%$ up to a distance approximately one fourth of the raft width]. This beneficial coupling contribution is even more evident focusing on the same plots at a settlement of 100% of pile diameter [Fig. 3(d)−(f)], where the PR strain/displacement pattern is significantly different than the combined PG and UR. The two mechanism are interacting among each other, involving a volume of soil significantly larger than the sum of the two separated mechanism. The previously described behaviour is even more evident in terms of displacements: the system seems to translate as a rigid block, composed by the foundations and the entire region enclosed by the piles. This is due to the presence of the piles under the raft, limiting the development of strains within the soil between the piles.

For foundations on granular materials, bearing capacity is unlikely to be a design concern (Viggiani *et al.*, 2014) and piles are employed as settlement reducers. In Fig. 4, the ratio between piled raft settlements ($u_{z,PR}$) and the corresponding raft ones ($u_{z,UR}$) is plotted as a function of the ratio between vertical load and UR limit load. In the worst condition, the settlements ratio is approximately 50%, implying that the PR stiffness is approximately double of the UR. In the same figure, the settlement ratio between PR and PG ($u_{z,PG}$ are the PG settlements) are also plotted. As expected, PR is always stiffer compared to PG. The settlement ratio ranges approximately between 45 and 60%, implying that the PR stiffness is approximately double. This suggests that that not accounting for the raft will result in a large underestimation of foundation stiffness.

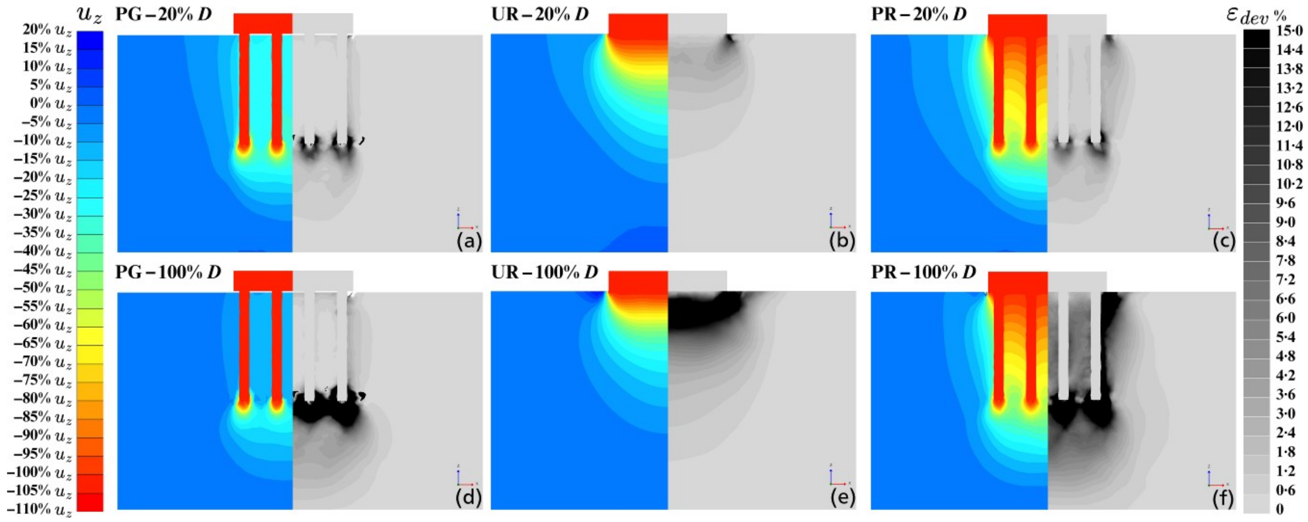


Fig. 3. Vertical displacement (left in colours) and deviatoric strain (right in grayscale) contour

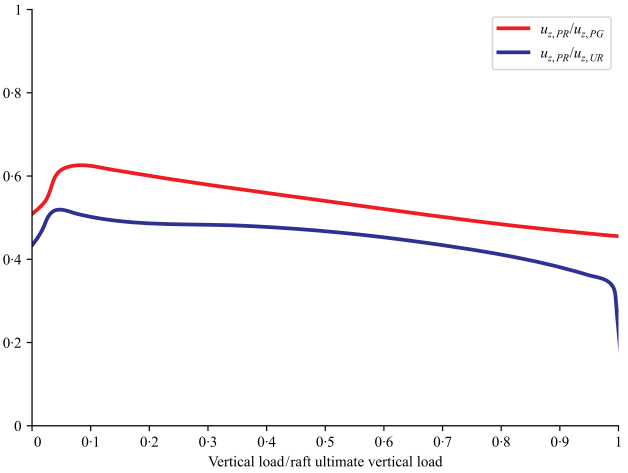


Fig. 4. Variation of settlement ratios with applied load

CONCLUSION

In this paper, the authors present the results of numerical simulations aimed at comparing the response of a piled raft with the one of corresponding unpiled raft and pile group. These simulations are part of a wider experimental/numerical programme aimed at introducing innovative solutions for piled raft design. The main objective of these numerical analyses was to design centrifuge tests. However, the numerical results for this case also highlighted:

1. As expected, the piled raft response is better than pile group and unpiled raft, with a stiffness that is almost always at least double.
2. The piled raft does not reach failure, implying that its limit load has to be defined on the basis of admissible displacement (displacement-based design).
3. Due to the raft–piles–soil interaction, the mechanical behaviour of the piles in the piled raft is better than that of the corresponding pile group.

These findings highlight the need for updated design guidelines that accurately account for raft contributions in piled foundations. Implementing such guidelines could lead to more efficient and economical designs, potentially reducing material usage and construction costs while maintaining or improving foundation performance.

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REFERENCES

Brinkgreve, R. B. J., Engin, E. & Engin, H. K. (2010). Validation of empirical formulas to derive model parameters for sands. In *Numerical methods in geotechnical engineering Numge 2010* (eds T. Benz and S. Nordal), pp. 137–142. London, UK: CRC Press.

Chanda, D., Saha, R. & Haldar, S. (2020). Behaviour of piled raft foundation in sand subjected to combined VMH loading. *Ocean Engineering* , 107596.

Corigliano, M., Flessati, L. & di Prisco, C. (2023a). Finite Element Analyses of Piled Foundations: Interaction Domains Under Undrained Conditions. In *National Conference of the Researchers of Geotechnical Engineering* (pp. 646–653). Cham: Springer Nature Switzerland.

Corigliano, M., Flessati, L., Bongio, P., D’Angelantonio, M. & di Prisco, C. G. (2023b). Numerical push-over analysis of a bridge piled foundation: geotechnical and structural verification. *Rivista Italiana di Geotecnica* , No. 2.

de Sanctis, L. & Mandolini, A. (2006). Bearing capacity of piled rafts on soft clay soils. *J Geotech Geoenviron Eng* , No. 12, 1600–1610.

Deb, P. & Pal, S. K. (2019). Numerical analysis of piled raft foundation under combined vertical and lateral loading. *Ocean Engineering* , 106431.

Fleming, K., Weltman, A., Randolph, M. & Elson, K. (2008). *Piling engineering*. Boca Raton, FL: CRC Press.

Han, F., Salgado, R., Prezzi, M. & Lim, J. (2019). Axial resistance of nondisplacement pile groups in sand. *J Geotech Geoenviron Eng* , No. 7, 04019027.

Hanisch, J., Katzenbach, R. & König, G. (2002). *Kombinierte Pfahl-Plattengründungen*. Berlin: Ernst & Sohn.

Hooper, J. A. (1979). *Review of behaviour of piled raft foundations.* CIRIA report n 83.

Horikoshi, K. & Randolph, M. F. (1996). Centrifuge modelling of piled raft foundations on clay. *Geotechnique* , No. 4, 741–752.

Katzenbach, R. & Choudhury, D. (2013). *ISSMGE Combined Pile-Raft Foundation Guideline*. Deep Foundations Institute.

Katzenbach, R., Arslan, U. & Moormann, C. (2000). Piled raft foundation projects in Germany. In: *Design applications of raft foundations*. (ed J.A., Hemsley) London: Thomas Telford, pp. 323–391.

Lee, S. H. & Chung, C. K. (2005). An experimental study of the interaction of vertically loaded pile groups in sand. *Can.*

Geotech. J. , No. 5, 1485–1493, https://doi.org/10.1139/t05-068.

Mandolini, A., Russo, G. & Viggiani, C. (2005). Pile foundations: Experimental investigations, analysis and design. *Ground Engng* **38**, No. 9, 34–35.

Marveggio, P., Corigliano, M., Ovalle-Villamil, W., Flessati, L. & Cabrera, M. (2024). Physical modelling of piled foundation under combined loading: insights on the piles-raft-soil coupling, proceedings of 5th European conference on Physical modelling in geotechnics, Delft, 2-4 Oct.

Nguyen, D. D. C., Jo, S. B. & Kim, D. S. (2013). Design method of piled-raft foundations under vertical load considering interaction effects. *Comput. Geotech.* , 16–27.

Psychari, A. & Anastasopoulos, I. (2022). Combined loading of RC pile groups in clay accounting for N–M interaction. *Soil Dynamics and Earthquake Engineering* , 107490.

Reul, O. & Randolph, M. F. (2003). Piled rafts in overconsolidated clay: comparison of in situ measurements and numerical analyses. *Geotechnique* , No. 3, 301–315.

Sakellariadis, L. & Anastasopoulos, I. (2022). On the mechanisms governing the response of pile groups under combined VHM loading. *Géotechnique* (in press).

Salgado, R. (2008). *The engineering of foundations*. New York: McGraw-Hill.

Sawada, K. & Takemura, J. (2014). Centrifuge model tests on piled raft foundation in sand subjected to lateral and moment loads. *Soils and Foundations* , https://doi.org/10.1016/j.sandf.2014.02.005.

Schanz, T., Vermeer, P. & Bonnier, P. (1999). Formulation and verification of the Hardening-Soil Model. Beyond 2000 in Computational Geotechnics.

Sommer, H., Tamaro, G. & De Benedettis, C. (1991). Messe Turm, foundations for the tallest building in Europe. In Proc. 4th Int. Conf. on Piling and Deep Foundations (pp. 139–145).

Tradigo, F., Mussi, A., Petrella, F. & Pisanò, F. (2017). Settlement prediction and monitoring of a piled raft foundation on coarse-grained soil: the case of the Allianz Tower in Milan.

Van Impe, W. & De Clerq, Y. (1995). A piled raft interaction model. *geotecnia*, No. 73, 01–23.

Viggiani, C., Mandolini, A. & Russo, G. (2014). *Piles and pile foundations*. CRC Press.

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