Structural and geotechnical design of a piled raft for a tall building founded on granular soil

Conception géotechnique et structurelle du radier sur pieux d'un bâtiment de grande hauteur fondé sur des sols granulaires

Allievi L., Ferrero S., Mussi A., Persio R., Petrella F.
Arup

ABSTRACT: The process followed in designing the piled raft foundation of a tall building is discussed. This entails analysing the governing limit states, assessing the geotechnical characterisation of the soil deposit as well as deploying the appropriate modelling tool to study the behaviour of the chosen foundation system at each design phase. Non-uniform loading imposed by the superstructure, long-term creep effects for deeper soil layers and reinforced concrete elements, cyclic actions associated with wind loading and pile-raft connection detailing also influence the design process. As the design of this piled raft is mainly differential settlement governed, the interaction between the structural and geotechnical design is of the utmost importance.

RÉSUMÉ: On présente la démarche suivie dans la conception du radier sur pieux d'un bâtiment de grande hauteur. Cela implique l'analyse des états limite, la validation de la caractérisation géotechnique des sols ainsi que la mise en œuvre des outils de modélisation appropriés pour étudier le comportement du système de fondation choisi à chaque étape des études. Les charges variables induites par les superstructures, les effets de fluage long terme des couches sous-jacentes du sol et des éléments en béton armé, les actions cycliques associés aux charges de vent, ainsi que les spécificités de la connexion radier-pieux, sont autant d'éléments qui interviennent également dans le processus de conception. Comme la conception de ce radier sur pieux est principalement contrôlée par les tassements différentiels, l'interaction entre la conception géotechnique et celle de la structure est de la plus haute importance.

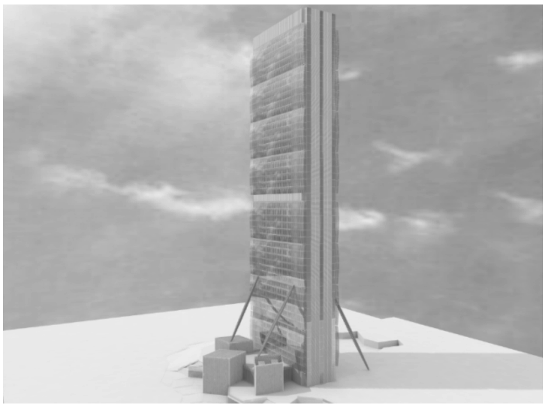
KEYWORDS: piled raft, settlement reducing piles, differential settlement, cohesionless soils

1 INTRODUCTION

Unlike conventional rafts or fully piled foundations, piled rafts are composite structures consisting of three bearing elements: piles, raft, and subsoil. The Isozaki Tower foundation falls under the category of "large piled rafts" and requires, according to Mandolini 2003, "differential settlement based design"; it is considered a "raft-enhanced pile group" as per the definitions given by Burland *et al.* 2012.

2 THE ISOZAKI TOWER

The Isozaki tower located in Milan comprises 52 storeys and has a total height of 202.2m from ground level (Figure 1).



© Arata Isozaki & Associates and Andrea Maffei Architects

Figure 1 General view of the Isozaki Tower

Use is primarily offices with a few areas reserved for services. In plan the tower is approximately 54.8m long by 22.5m wide. The reinforced concrete raft is 2.5m to 3.5m thick and is supported by 10 no. 1.5m diameter piles and 52 no. 1.2m diameter piles. The piles are bored cast in-situ and 33.2m in length.

The unfactored total load applied at the base of the tower is 1350MN (Figure 2). Considering a raft footprint of 63.1m x 27.0m, the equivalent bearing pressure on the ground is 860kPa, including the raft self-weight.

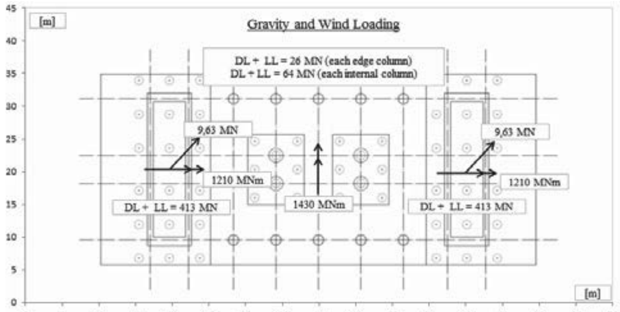


Figure 2 Piled-Raft foundation plan and loading.

3 GROUND CONDITIONS

The site is situated within the Padana Plain in northern Italy, underlain by a 100m thick deposit of Quaternary alluvial granular material. This consists of a normally consolidated coarse sand and gravel unit with the original ground level at +124m asl. The extensive site investigation (SI) included borehole drilling, down hole SPT and pressuremeter tests, permeability tests as well as a pumping test. The SI also comprised a set of geophysical investigations. Undisturbed samples collected from the cohesive layers were subject to oedometer tests and triaxial tests.

Within the granular deposit, three interbedded layers of clayey silts with a PI of 10-30% are found at +79m asl (layer D), +59m asl (layer F) and +45m asl (layer H) with a thickness of 3m, 4m and 2m respectively (Figure 3).

The cohesionless layers typically have a relative density of 45-65% and ϕ'_{cv}=36°. The soil stiffness profile at small strains was derived from V_S measured in situ; a good agreement with the empirical correlation to N_{SPT} values proposed by Stroud (1988) was found for the granular materials. For the cohesive layers, the secant stiffness was estimated from c_u and OCR according to Koutsoftas and Fisher 1980.

The two level basement requires a 16m deep excavation, so the raft formation level is at +108m asl. Extensive aquifer exploitation lowered the groundwater table from +120m asl to a minimum level of +100m asl in the mid 70's. With the relocation of industrial sites outside the urban area the groundwater table has risen to the current level of +106.5m asl, resulting in a lightly overconsolidated deposit, with OCR values ranging between 1.35 and 1.20 in the cohesive layers D to H.

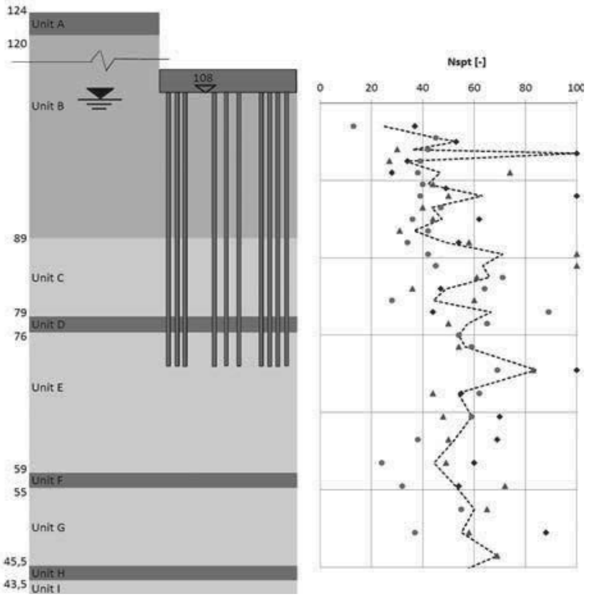


Figure 3 Stratigraphy and SPT tests profile (levels in metres asl)

4 FOUNDATION DESIGN

The Italian Construction Code (2008) covers mixed foundations and determines that where the raft alone is capable of satisfying the ULS, the piles can act as settlement reducers and their design should ensure the satisfaction of the SLS. This implies that the piles need to be checked for the structural limit states only.

The main design challenges consisted in accounting for the presence of deep cohesive layers and achieving a cost-effective solution. The absence of published data on the behaviour of existing high-rise buildings founded on mixed foundations in Milan is noted.

The structural and geotechnical design was developed in phases, with simplified methods being used for preliminary design (Poulos 2001; Mandolini *et al.* 2005).

From early design stages it was found that an unpiled raft could carry the load shed from the superstructure alone. The corresponding stresses, however, require a very thick and heavily reinforced raft which is not the most cost-effective or buildable foundation solution. Similarly, there was no feasible configuration for a fully piled solution, considering the pile length constraints explained below. The behaviour of an unpiled raft foundation solution was analysed to guide the selection of the settlement reducing pile locations and control the raft stresses and differential settlements (Figure 4).

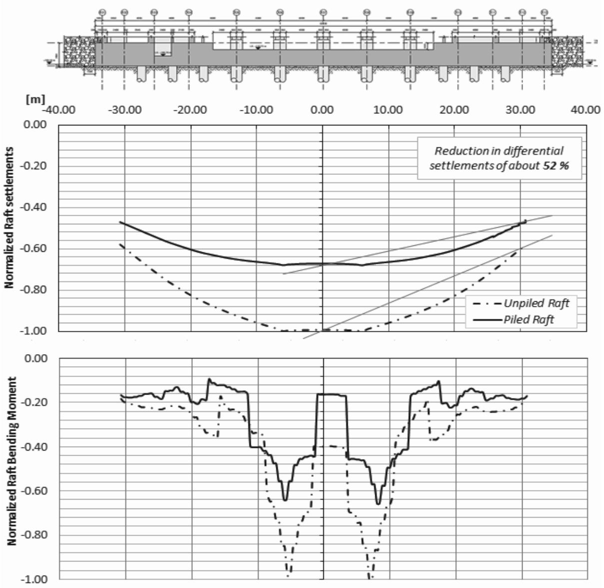


Figure 4. Unpiled Raft vs Piled Raft: Settlement and Bending Moment diagrams normalized to the unpiled raft maximum values.

Creep settlements of the cohesionless layers where estimated according to Burland & Burbidge 1985 for a design life of 100 years.

Due to permeability of cohesive layers ranging between 10^{-8}m/s (layers D and H) and 10^{-9}m/s (layer F) and their limited thickness it was evaluated that primary consolidation should take place during construction (assumed > 2 years). The secondary consolidation coefficient was estimated from *ad hoc* oedometer tests subject to a longer than standard duration (6 days ≈ one additional log-cycle) at the relevant design effective stress. The aim of limiting the impact of creep associated to the cohesive layers, led to positioning the pile base just below the cohesive layer D. This corresponds to a pile length to radius of equivalent circular foundation area ratio of 1.4 which, together with the pile group-raft area ratio, is identified as the most effective elements of the system geometry for the minimisation of the normalised differential settlements (Reul & Randolph 2004).

During the first phases of design the single pile axial resistance and load-settlement curve were estimated using the $K_s \cdot \tan\delta$ approach and the method proposed by Fleming 1992, respectively. The final design stage benefited from the availability of site-specific preliminary pile load tests which showed an average unit shaft resistance ranging between 90 and 120kPa and provided load-settlement curves for the calibration of the FE models. The piled-raft was analysed with the FEM software Oasys GSA 2010 which links the superstructure, foundation and ground into a single soil-structure model. The raft was modelled with 2D shell elements in contact with beam elements (piles) and a linear elastic soil mass within which displacements are calculated according to the Mindlin method. Each pile node has an associated pile-soil interaction coefficient curve which enables a non-linear response of the pile under vertical loading. The soil stiffness was developed considering the part of the load occurring in re-loading conditions and that in virgin compression as well as the estimated average soil shear strain (γ=0.1%) derived from the stiffness degradation curves proposed by Seed & Idriss 1970 for cohesionless soils.

The GSA model was compared with a full 3D FE analysis developed with MIDAS GTS (Figure 5) which provided similar settlements, pile axial loads and raft stresses.

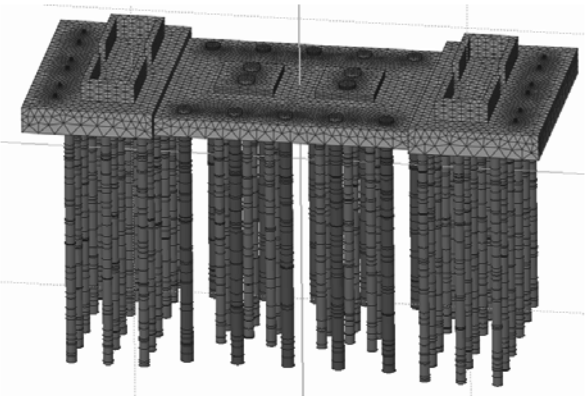


Figure 5. MIDAS GTS 3D FE model of the piled raft.

Creep effects of the concrete in the raft and piles were taken into account as these affect the long term behaviour of the foundation. A reduction factor of the young modulus of $1+\varphi_\infty$ was adopted with φ_∞=0.90 for the raft and 0.76 for the piles. In order to limit bending moments in the top of the piles due to raft deflection, no structural connection between the raft and the pile head was provided.

The piled raft behaviour under horizontal loads was analysed with PIGLET (Randolph 2006) and the Oasys software ALP and PDISP.

The effect of wind induced cyclic actions was estimated according to the methods described by O'Riordan 1991 (settlements) and Poulos & Davids 2005 (pile stiffness degradation).

Half of the maximum raft settlements were estimated to occur during construction, 33% were associated to creep, 13% to cyclic loading and 4% to planned nearby buildings. The potential for tilting due to variations in thickness of the cohesive layers was estimated to be negligible.

The load percentage split between the raft and the piles estimated from the FE analyses is 35/65: this matches well with that proposed by Mandolini *et al.* 2005 for $(s/d)/(A_g/A)$=4.75.

The 1.2m diameter piles have a factor of safety (FoS) ranging between 1.45 and 1.65, and the 1.5m diameter piles between 1.55 and 1.75.

Whilst stringent checks of pile construction (eg. cleaning of the base) are needed to ensure that the specified requirements are met, limiting the mobilisation of the piles shaft resistance minimises the sensitivity of the raft behaviour with respect to workmanship problems and local variations of soil conditions.

Accepting a FoS<2 for the piles required the use of a higher concrete class (C32/40) than in conventional piled foundations: this has cost implications and needs to be considered at optioneering stage. The overall cost of the piled raft was estimated to be 35-45% lower than that of a simple raft; the piled raft requires 50-60% less concrete and 35-45% less steel. The cost of the piles is 20% of the total foundation cost.

The piled raft has been constructed and is fully instrumented.

5 CONCLUSIONS

Mixed foundations are covered by the Italian Construction Code which allows the design of piles as settlement reducers if the raft alone can comply with the ULS requirements.

Simplified methods are used during the initial optioneering phase to develop a solution which can then be analysed with more rigorous tools.

GSA is a reliable and efficient tool for the final design stages which has shown to match the results of a parallel full 3D FE piled raft model.

Pile length to equivalent circular raft radius ratio and pile group-raft area ratio are important elements to consider during design.

A FoS<2 on piles results in higher working load in piles than would otherwise be the case; this requires additional consideration for their structural design.

Internal actions on the upper part of the piles are reduced by avoiding a structural connection between piles and raft without significantly affecting the raft behaviour. Limiting the mobilisation of the piles' shaft resistance minimises the sensitivity of the raft behaviour with respect to workmanship problems and local variations of soil conditions.

Assessment of the total settlements requires consideration of time-dependant phenomena.

Piled rafts can offer a cost-effective foundation solution for high-rise buildings.

6 ACKNOWLEDGEMENTS

The authors would like to thank Duncan Nicholson, Alessandro Baliva, and Matteo Minno for their contribution as well as Marco Beccati for his support from the client's side.

7 REFERENCES

Burland and Burbidge 1985. Settlement of foundations on sand and gravel. Proc. ICE, part 1.

Burland J., Chapman T., Skinner H. D. and Brown M. 2012. Manual of Geotechnical Engineering, Institution of Civil Engineers.

Decreto Ministeriale 14.1.2008 del Ministero delle Infrastrutture. "Nuove norme tecniche per le costruzioni". S.O. n. 30 alla G.U. del 4.2.2008, n. 29.

Fleming G.W.K. 1992. A new method for single pile settlement prediction and Analysis, Geotechnique 42, No. 3 pp 411-425

Koutsoftas, D., Fisher, J. 1980. Dynamic properties of two marine clays, ASCE J. Geotech Division 106 (GT6), pp. 145-157.

Mandolini A. 2003. Design of piled raft foundations: Practice and Development, Design of foundations on bored and auger piles, Van Impe ed., Rotterdam.

Mandolini A., Russo G. and Viggiani C. 2005. Pile Foundations: Experimental investigations, analysis and design. *ICSMGE*, Osaka.

MIDAS GTS Scientific Manual.

Oasys Ltd, Oasys Geo Suite v 19.1 ALP, GSA and PDISP Software Manual, London 2010.

O'Riordan N.J. 1991. Effects of cyclic loading on the long term settlements of structures, Cyclic loading of soils, Blackie.

Poulos H. G. 2001. Piled-raft foundation: design and applications. Geotechnique, 51(2), 95-113.

Poulos H. G. and Davids A. J. 2005. Foundation design for the Emirates Twin Towers Dubai, Canadian Geotechnical Journal, 42, 716-730.

Randolph M.F. 2006. PIGLET: Analysis and design of pile groups. Users' Manual, Version 5.2, Univ. Western Australia, Perth.

Reul O. and Randolph M.F. 2004. Design strategies for piled rafts subjected to nonuniform vertical loading, Journal of Geotechnical and Geoenvironmental Engineering, ASCE.

Seed H. and Idriss I. 1970. Soil moduli and damping factors for dynamic response analysis. EERC report n.70-10. Berkeley, CA.

Stroud, M.A. 1988. The standard penetration test – its application and interpretation.