Piled Rafts in New York City-Design Overview and Case History

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ABSTRACT

Piled-raft foundations provide significant financial advantages in situations where the subsurface conditions provide adequate bearing capacity, but the raft foundation alone produces excessive settlements. However, the use of piled-rafts remains challenging in many urban environments because of building code constraints, and lack of experience by both geotechnical and structural engineers. This paper presents a geotechnical consultant’s approach to the design of piled-raft foundations for high-rise structures, followed by a case history in New York City. The design process is described starting first with feasibility study, followed by a preliminary piled-raft design based on published procedures, and finally the use of numerical modelling to capture the soil-structure interaction of this complex system. The case history for “167 Johnson”, a 36-story structure in Brooklyn, N.Y. is discussed.

1. INTRODUCTION

Traditionally, deep foundations are used when shallow foundations do not meet bearing capacity or settlement requirements, and the superstructure loading is assumed to be carried entirely by the pile elements. However, in situations where settlements are excessive but the raft foundation has adequate bearing capacity, a more economical design can be achieved with the use of a piled-raft system. Piled-rafts foundations consist of a raft where the overall system’s performance is enhanced by adding a limited number of piles acting as “settlement reducers” and located strategically below the heavily loaded portions of the raft. These settlement reducing piles can be designed to carry loads close to their ultimate capacity as long as the combined piled-raft system has an adequate bearing capacity against failure.

The use of piled-rafts has been used in numerous projects worldwide and studied extensively by numerous researchers (e.g.: Burland et al. (1977), Katzenbach et al. (1997, 2005, and 2006), Hemsley (2000), Poulos (2001 and 2002), Badelow et al. (2006) among many others. However, settlement reducers have had very limited applications in the US (O’Neill, 2006), and never applied for a high-rise structure in New York City. This limited application is attributed to lack of knowledge by practicing engineers, as well requirements of the local building codes, which frequently require a factor of safety on individual piles design of at least 2, and thus indirectly limiting the use of a piled-raft system.

This paper presents the steps followed by the geotechnical consultant in the design of a piled-raft foundation in New York City, as well as description of the case history results and steps in obtaining realistic soil parameters for numerical modelling.

2. DESIGN CONCEPTS

The design of a piled-raft system requires the consideration of a number of geotechnical and structural issues, as is the case for any foundation system, including (Poulos, 2001):
(a) ultimate vertical and lateral capacity of the combined system, (b) maximum settlement, (c) differential settlement and angular distortion, (d) raft moments and shear for structural design, and (e) pile loads and moments for structural design.

The design process can be divided into three parts: (a) feasibility study to assess whether the use of a piled-raft system may potentially satisfy the design requirements, (b) a preliminary piled-raft design using a combination of simplified published procedures and simplified finite element (FE) analyses, and (c) final numerical analysis considering all the pile locations, and estimation of final pile and raft loads. These steps are described in the subsequent sections.

Feasibility Study

Effective applications of piled-rafts occur when the raft alone can provide adequate capacity, but the settlements and differential settlements exceed the design values
Poulos, 2001). As such, soil profiles consisting of stiff clay or dense sands are generally favourable for piled-raft applications, whereas those consisting of soft and loose materials are generally not feasible.

During the feasibility stage, the bearing capacity of the individual pile and raft components is computed to determine whether the combined system satisfies the load requirements. The ultimate bearing capacity of a piled-raft is typically given by the following Eq. (1) (Katzenbach, 2005):

\[ R_{\text{tot}} = \sum R_{p_{ik},i} + R_{\text{raft}} \]  

(1)

where, \( R_{p_{ik},i} \) and \( R_{\text{raft}} \) are the ultimate bearing capacity of the piled-raft, individual piles, and individual raft, respectively.

Where \( R_{\text{tot}} \) has an adequate factor of safety compared to the total superstructure load, the piled-raft system can be assumed to be feasible. However, advanced analyses are required to determine whether a limited number of piles would satisfy the serviceability requirements.

### Preliminary Piled Raft Analysis

A detailed piled-raft design is typically a lengthy process and considers a variety of parameters such as: a) pile diameter; b) pile length; 3) pile spacing; and 4) pile locations. In addition, sensitivity analyses should be performed on each of the parameters to determine the most effective contribution. However, for early design stages, a preliminary analysis can be performed using finite element analysis by modelling the piles as a “block” of improved soil (Fig. 1), as opposed to modelling the piles at precise locations.

![Fig. 1: Cross Section Showing a “Block” Model](image)

A parametric study can then be performed more readily by varying the stiffness of the “block”, as well as its extents. The corresponding number of piles for each “block” stiffness can be back-calculated from the following Eq. (2):

\[ N_p = \frac{E_s \times A_b - E_s \times A_s}{E_p \times A_p} \]  

(2)

Where, \( N_p \) is number of settlement reducers, \( E_s \) is the E modulus of the “Block”, \( E_s \) is E modulus of the soil, \( A_b \) is the area of the “Block”, \( A_s \) is the area of individual settlement reducer, and \( A_p \) is the plan area of soil.

In addition, commercial piled-raft spreadsheets are available and estimate settlements for piled-raft systems for idealized conditions, based on published procedures in the literature. While those spreadsheets, such as the one developed by Lee et al. (2005) at Virginia Polytechnic and State University, do not consider three dimensional effects, varying subsurface conditions and asymmetric loading, they provide insight on the approximate percentage settlement reduction obtained for similar conditions for an individual raft and can thus be very helpful. The Lee et al. (2001) spreadsheet was used in the 167 Johnson case-histories, as will be described in a subsequent section.

### Final Piled Raft Analysis

The final piled-raft analysis incorporates all the findings of the preliminary analysis, mainly the approximate location and number of piles needed to achieve the prescribed settlements and differential settlements goal. Ideally, field load tests, such as pile and/or footing load tests should be performed to calibrate the soil parameters used in the final element model. By obtaining real field data, the field test can be modelled and parameters varied as necessary to replicate the observed results and gain more confidence in the parameters used (Holman et al., 2006).

The outcome of the final analysis consists of the estimated serviceability of the raft, as well as estimated loads and parameters needed for the structural design of the mat. The location of the piles can significantly impact bending moments within the raft, and as such, this final step of determining the optimal location of the piles should be performed with close collaboration between the structural and geotechnical engineers.

### 3. CASE HISTORIES

Detailed three-dimensional finite element analyses were performed for two high-rise structures in Brooklyn, N.Y. The FE analyses were performed using the commercially-available software Plaxis 3D Foundation (Plaxis 3D).

In general, the subsurface soils in New York City and its outlying boroughs are primarily the result of repeated glaciations and ice advancement during the Pleistocene Era. In Downtown Brooklyn, where the “167 Johnson” and “Brooklyn” structures are located, the site area is underlain by a glacial deposit known as ground moraine. This deposit is a widespread dense layer, consisting mostly of a mixture of dense sand, silt and boulders overlying bedrock, which is typically at about 45 m below sidewalk grades. The following subsections describe the details of the analyses performed for the final piled-raft design for the two case histories.

**Case History 1: 167 Johnson, Brooklyn, N.Y.**

The development consists of a residential building with a two-story podium and a cellar level, topped by a 35-story structure at the centre of the structure. The building footprint is fairly rectangular in shape, about 52-m-long by 30-m-wide and covers the entire site.
The project’s subsurface investigation consisted of performing nine borings, in accordance with the requirements of the New York City Building Code. The borings were extended 3 m into bedrock. Figure 2 shows an idealized subsurface profile and the SPT $N_{60}$-values with depth.

**Fig. 2: Idealized Subsurface Profile and SPT $N_{60}$-Values**

**Preliminary Geotechnical Assessment**

The total load of the structure was estimated at about 310 MN, with a corresponding average bearing pressure of about 240 kPa. Over 35% of the total loads were carried by the shear walls at the center of the tower within an estimated localized bearing pressure of over 750 kPa.

A preliminary analysis was performed to estimate the performance of a continuous raft foundation. Conventional geotechnical engineering analysis and a FE analysis indicated maximum estimated settlements on the order of 4 to 6 cm beneath the tower core, about 2 to 3 cm at the tower edges and less than 1 cm at the corners. The corresponding angular distortion of the raft was estimated at about $1/350$. While the soil could provide adequate bearing capacity to support the structure, the structural engineer requested that the angular distortion be lowered than $1/500$. Therefore a continuous raft foundation was not feasible and an alternate foundation system was required.

**Preliminary Piled-Raft Analysis**

The geotechnical engineer proposed the use of a raft foundation below the building tower combined with isolated spread footings to support the relatively light perimeter columns. To reduce the differential settlements, a limited number of settlement reducers would be strategically located below the heavy tower core. To obtain a preliminary estimate of the total settlements using a piled-raft, the geotechnical engineer used the Lee et al. (2005) spreadsheet. Given the limitations of the analysis described previously, only the core area with shear wall loads was modeled. The analysis showed about 5 to 6 cm of settlements for the raft foundation, and about 3.5 to 4 cm when using 20 to 25, 30 MN, 30-cm-diameter piles or “Ground Improvement Elements”. Figure 3 shows the reduction in total settlements with the number of piles: the total settlement reduction is not significant for more than piles.

**Fig. 3: Preliminary Estimate of Settlement Reduction with Number of Piles**

Preliminary modeling confirmed the results of obtained using the spreadsheet approach. However, as with all modeling, the results are a reflection of the quality of the input parameters. Therefore the geotechnical engineer recommended two full-scale instrumented load tests in order to verify the geotechnical capacity of the piles and obtain calibration parameters for the soil properties used in Plaxis 3D. Details of the load tests are described in Holman et al. (2006).

**Calibration of FE Model Based on Pile Load Tests**

Each load test was modeled individually with bond lengths of 6 m and 10 m for test piles 1 and 2, respectively. The piles were modeled in Plaxis 3D using the “Massive Circular Piles” option, which correspond to circular volumetric elements with equivalent linear-elastic properties. The model load was applied to the piles in increments to duplicate the field loading schedule and the results were used to generate load settlement plots, as seen in Figure 4.

The results obtained in Plaxis 3D matched the field results closely. The cyclic loading was not modeled in Plaxis 3D since “Mohr-Coulomb”, a linear-elastic-perfectly-plastic model was used and cannot handle soil softening due to cyclic loading. The close match between modeled
and observed results showed that the soil parameters used in Plaxis 3D are representative of actual in-situ conditions. In addition, the pile-soil interaction and load transfer mechanism observed in the field is well represented in Plaxis 3D Model.

![Fig. 4: Modelled Versus Observed Load Test Results](image)

**Final FE Analysis**

A detailed FE assessment using the calibrated raft foundation was performed. The analysis confirmed the preliminary analysis observation that about 20 to 25 piles strategically located below the tower shear walls, as shown in Figure 5, reduces differential settlements to acceptable levels.

![Fig. 5: Final Plaxis 3D Model Showing the Settlement Reducers Below the Tower Core](image)

4. CONCLUSIONS

This paper presents an overview of the steps required for piled-raft design, and a design-based load testing program and subsequent analysis of a piled-raft foundation. The approach, although previously used in projects worldwide, had never been applied in New York City, and is still not considered a traditional alternative to deep foundations, despite the significant financial advantages.

**REFERENCES**


