

Importance of the Excavation Level on the Prediction of the Settlement Pattern from Piled Raft Analyses

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Abstract. This article analyses the effect of the excavation level on the settlement results from a standard analysis of a piled raft system. For that, a published case history that involved a house located in Gothenburg, Sweden by Hansbo (1993) was examined. This structure was founded over a soft, highly plastic marine clay of varying thickness, where the foundation was designed by using the concept of “creep piling”, *i.e.*, piles in a state of full load mobilization. The analyses were carried out with the numerical tools DEFPIG and GARP, by considering a series of simplified assumptions for the load pattern, raft and pile characteristics and subsoil profile. The soil, pile and load characteristics have been considered, with analyses that allowed (or not) the effect of the excavation level. The exercise emphasizes the importance of such consideration for the assessment of the settlement pattern underneath the raft. This contribution concludes that it is not possible to precisely predict the behavior of piled rafts without a full understanding of its important input parameters, such as the excavation depth. It should be of considerable interest for those who design / simulate piled foundations and need to predict their performance in the presence of consolidating soft soils.

Keywords: foundation design, numerical analysis, piled raft, soft clay, soil excavation.

1. Introduction

In the past decade, several papers have been published with emphasis on what are now called as “piled-rafts”, *i.e.*, pile groups in which the raft connecting the pile heads positively contributes to the overall foundation behavior (for example Ottaviani, 1975; Poulos, 1991; Hansbo, 1993; Burland, 1995; Ta & Small, 1996; Clancy & Randolph, 1996; Mandolini & Viggiani, 1997; Poulos, 1998 and Cunha *et al.*, 2001). The International Society for Soil Mechanics and Foundation Engineering (ISSMFE) also focused the activities of one of its Technical Committees (ITC-18) on the study of piled raft foundations. This Committee gathered valuable information on case histories and on methods of analysis, having produced comprehensive reports on these activities (O’Neill *et al.*, 1996).

In regard to the design philosophy of piled rafts, Randolph (1994) has defined the following approaches:

- The “conventional approach”, in which the foundation is designed essentially as a pile group to carry the major part of the load, while making some allowance for the contribution of the raft. This is the conventional approach widely adopted in design;
- The “creep piling approach”, as proposed by Hansbo & Källström (1983), in which the piles are designed to operate at a working load at which significant creep starts to occur, typically 70-80% of the ultimate load capacity. In this case, the pile cap or raft, contributes to the overall capacity;

- The “differential settlement approach”, in which the piles are located strategically in order to reduce the differential settlements, rather than to substantially reduce the overall average settlement. The pile cap, or raft, also contributes to the overall capacity.

In general, the latter two approaches are more economical than the first one, but they can only be used under certain conditions, where either local standard allows or differential settlements are the key design factor. Other papers have expanded upon these ideas, such as those by Cunha & Sales (1998) and Cunha *et al.* (2000a, b). Cunha & Sales (1998) described and discussed a paper describing and discussing field loading tests carried out in small scale footings supported by a reduced number of piles. These tests were performed at the University of Brasília research site, and have confirmed that this design methodology has a large potential (although with some restrictions) to be adopted with the collapsible porous clay of the Federal District of Brazil. Cunha *et al.* (2000b) analyzed a piled raft case history in the city of Uppsala, Sweden, on a prediction exercise very close to the one presented herein. They have suggested an “optimized” parametric procedure for the preliminary design of both piled rafts and standard deep foundations. This optimization has proved that it is possible to obtain a considerable cost saving in the final design, without detriment to the original factor of safety of the foundation. The suggested procedure has been tested against another case history in Sweden (Cunha *et al.*, 2000a), al-

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lowing the perception of the influence (in design) of one of the relevant variables that affect the behavior of the foundation system, *i.e.*, the number of piles underneath the raft. This latter paper established the basis of the presented numerical results, although the critical discussion and analyses have been considerably extended herein with information not available at that time. Therefore, the present exercise conveys a critical discussion on previous analyses by Cunha *et al.* (2000a), expanding their scope.

Thus this note explores the design of piled rafts, outlining the influence of the consideration (or not) of the excavation level on the proper assessment of the settlement of the piled raft system, including the excavation process in a very simplified manner. This technique is not new, and has already been adopted before by some authors as Sales *et al.* (2010) or Ibañez *et al.* (2014), among others. Sales *et al.* (2010) allowed for the influence of the variation of the stress level on the piled raft behavior in a rather complex manner, introducing the excavation sequence (stepwise) process on the numerical analyses in what has been called as a “compensated” piled raft analysis. On the other hand, Ibañez *et al.* (2014) considered the effect of the excavation with a more simplified procedure (like the one to be adopted here), simply by correcting the effective original stresses of the ground to the relief stress/reloading caused by both the extracted soil during excavation and the concrete raft molding. Both cases are simplified, and do not lead to perfect simulations of the real phenomena, but they can considerably improve the settlement pattern predicted by the numerical simulations. Of course, they cannot be precise given several other external aspects that are difficult (if not impossible) to input within the analyses, such as the stiffening and load distribution effects caused by the subsoil-superstructure interaction, the real rheological behavior of the soil upon unloading and reloading stages, the concrete placement and curing of the raft, the sequential (floor by floor) loading stages of the building, geotechnical variability of the subsoil and variable foundation geometries, concrete creep effects, and temperature effects among several others.

2. Material and Methods: Adopted Case History

Sweden is the biggest country in the Scandinavian region, covering an area of 450,000km². The dominant characteristics of the landscape can be attributed to glacial activity, with the rocky south-west coast along the Baltic Sea, and the Stockholm archipelago on the south-east coast, which is most notable for their fjords (as stated in the Lonely Planet web-page). Gothenburg is the Sweden’s second city, being situated on the country’s west coast in between Copenhagen and Oslo.

In the early 80’s, two quite similar houses, one founded on conventional friction piles and the other on a “creep-piled” raft foundation were constructed in this city.

These buildings, defined as “House 1” and “House 2”, were located just 20 m apart. House 1 was designed in full accordance with the Swedish Building Code, meaning that the total load of the building was assumed to be carried by the piles. These piles were designed with a safety factor of 3 against a short-term (undrained) failure. House 2, on the other hand, was designed with the “creep piling” approach, as proposed by Hansbo & Källström (1983). In this approach, the piles are loaded to values close to, or equal to their creep load. They have the main purpose of reducing the settlement of the overall foundation structure, since the load of the building is partially counterbalanced by the contact pressure at the soil / raft interface (Hansbo, 1993).

House 2 was chosen to be analyzed herein. This house was designed to be an apartment house with 4 stories. It had a plan area of approximately 1000 m² with total dimensions of 75 vs. 12 m, as schematically presented in Fig. 1. It was constructed with four levels and a basement, leading to a total design load of 61.5 MN. The whole building was cast-in-situ, with basement walls uniformly spread over the base area. It was also designed to rest on a piled raft with a 0.4 m thick raft foundation, directly resting on top of the local marine clay, *i.e.*, no clear mention by Hansbo (1993) is made regarding the fact that the foundation raft was buried or not in the site although a “basement” unit has been mentioned. Nevertheless, there are some indications in this original reference that the 4 story apartment houses 1 and 2 were very similar and both had a “basement”, as clearly described in the text. Besides, this reference, that indicates the ground beams for House 1, depicts what appears to be a basement space below the ground level. Hence, supported by indirect evidence, it is very probable that the foundation raft was indeed buried in the site, at least to one story level (~ 2.5 to 3 m) – and this is what it was assumed here.

In this piled raft foundation, 104 piles were used. They consisted of 0.3 m in diameter and 18 m long spliced timber “underpiles” with 8 m long 0.3 m diameter circular concrete piles on top. The total length of the composite piles was 26 m, being driven in place and uniformly spread over the building. They were placed mainly beneath the basement walls, as depicted by the filled circles of Fig. 1. It also shows the instrumentation that was placed prior to the casting of the raft. Pile load cells, contact pressure cells,

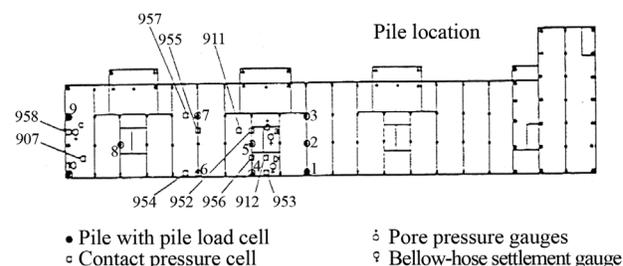


Figure 1 - House 2 – Gothenburg (modified after Van Impe, 1999).

bellows-hose (benchmark) settlement gauges, pore pressure gauges, and leveling stations were installed – as indicated in Fig. 1.

It should be pointed out that this case history was proposed by Van Impe (1999) to be one of the examples of an international exercise on the predicted behavior of piled rafts, via numerical programs. During this event, the instrumentation data was not made available to the participants, in order to characterize a “Class A” predictive exercise, although it was already known at that time that the settlement results of this case history had been previously published by Hansbo (1993). Indeed, as will be further detailed, some effort to truly perform a “Class A” prediction was made by the authors of the present contribution, by analyzing this case history solely on the basis of the data provided for the prediction exercise, together with the geotechnical characteristics of the site. Hence, “Class A” analyses are also presented and discussed in the present exercise, allowing it to highlight the importance of some of the parameters used for

the numerical simulation of piled rafts, in particular the excavation level.

3. Geotechnical Characteristics of the Subsoil

The subsoil at the test site consisted of soft, highly plastic marine clay of varying thickness. The clay was relatively homogeneous and contained two layers of silty clay, one at about 12 m and one just below 30 m, as graphically depicted in Fig. 2. This clay layer extended down to a depth of 55 m beneath the two houses, and was underlain by rock.

The undrained shear strength (S_u) was fairly constant along the profile, down to 10 m depth, with a mean value of about 20 kPa. It then increased linearly with depth, at an approximate rate of 2 kPa/m down to around 40 m depth. The sensitivity was quite constant, being slightly less than 20. The natural water content varied from 60 to 80%, and the liquid limit was usually somewhat higher. The plasticity index was typically about 50%, and the bulk density or total unit weight was around 16.5 kN/m³. The clay was slightly

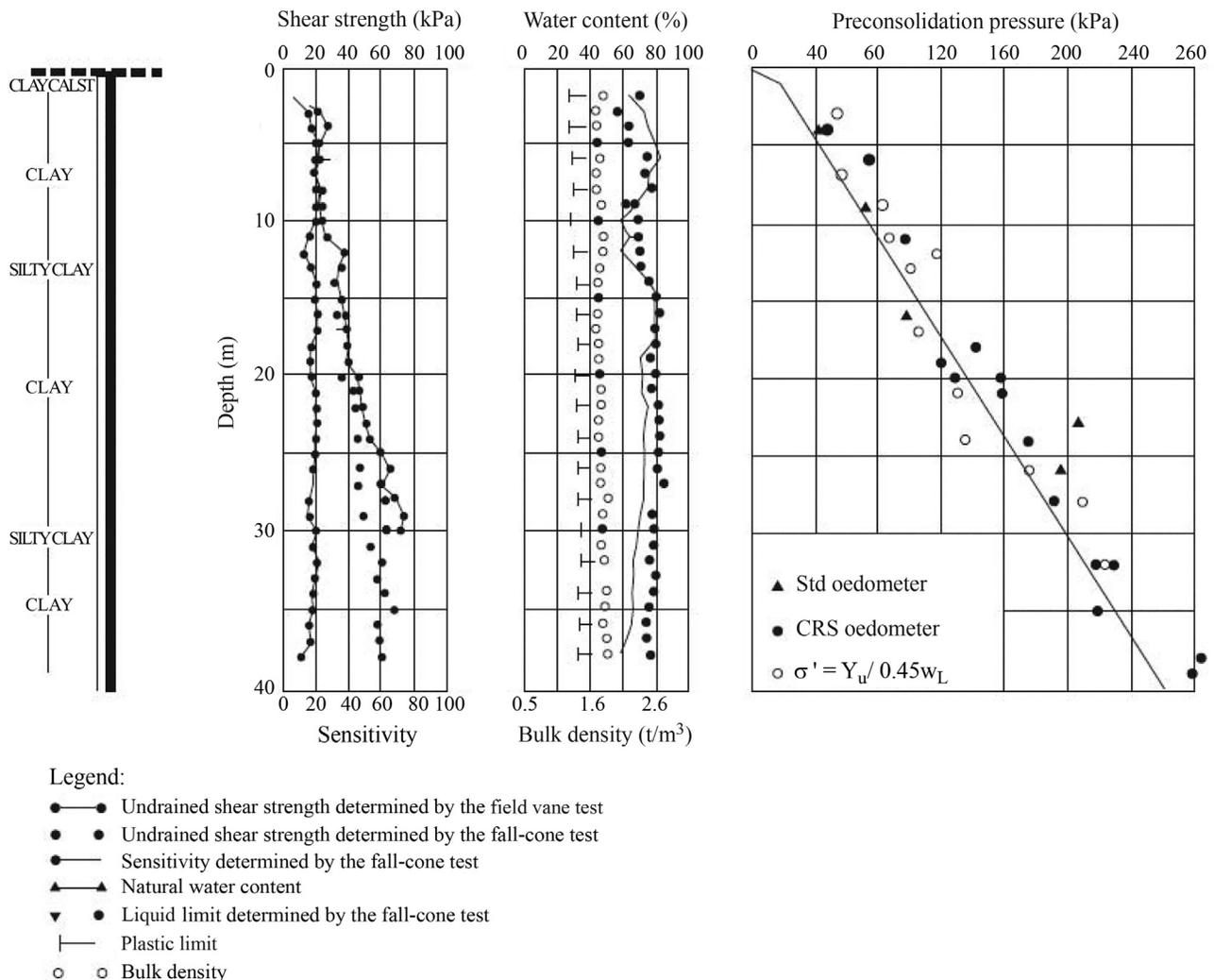


Figure 2 - Main geotechnical parameters of the subsoil (modified after Van Impe, 1999).

overconsolidated, given the fact that standard and CRS oedometer laboratory tests yielded preconsolidation pressures just above the values of vertical effective stress in the soil layer.

4. Numerical Tools and Assumptions for Analysis

The program GARP (Geotechnical Analysis of Raft with Piles, Poulos & Small, 1998) was adopted to evaluate the behavior of the rectangular piled raft foundation at Gothenburg that was subjected to a distributed vertical loading. It is based on a simplified form of a hybrid program in which the raft is represented as a linear elastic plate (via finite elements) and the soil can be modeled either as an elastic layered continuum or as a “Winkler” spring medium. The piles are represented by elastic-plastic springs that can interact with each other and with the raft. Limiting values of contact pressure (beneath the raft) and pile capacity can also be specified. By analyzing the raft using the finite element technique, rather than via finite differences, it is possible to numerically simulate irregular shaped rafts, which can also be subjected to uniform or concentrated loads.

As mentioned above, GARP also considers “interaction factors” between the springs that represent the piles. Such factors are computed via the use of another well-established software program DEFPIG (Deformation Analysis of Pile Groups, Poulos, 1990). This latter program determines the deformations and load distribution within a group of piles subjected to general loading. It was specifically written for piles designed using the “standard approach”, by considering a group of identical elastic piles having axial and lateral stiffness that are constant with depth. It also allows for the eventual slippage between the piles and the surrounding soil. The stress distributions are computed from the theory of elasticity, more specifically from Mindlin’s solutions for an isotropic, homogeneous, linear elastic medium. It can also consider, although in a simplified manner, the soil non-homogeneity along the length of the pile (*i.e.*, variation of the soil modulus with depth).

Both programs were used by adopting several simplified assumptions regarding the pile, raft and soil characteristics. These assumptions were necessary due to the simplified way in which these analyses were done, and also due to the lack of detailed information on this particular case history, as previously mentioned.

The following assumptions were made:

- Soil Profile: 55 m of soft to medium clay (average $S_u \approx 30$ kPa varying from 20 to 60), overlying a rock surface. GARP took into consideration the soil parameters (Young’s Modulus and Poisson’s ratio) down to this lower limit of depth, where an extremely rigid (rock) surface was adopted. A constant drained Young’s Modulus of 8200 kPa (lower limit) and 15000 kPa (upper limit) respectively were considered in the parametric analyses with the clay profile, together with a variable drained modulus (E ’s) increasing from 6600 to 11800 kPa). These values are applicable to driven piles in clay, and were estimated by adopting the correlation between shear strength and modulus expressed in Poulos and Davis (1980). A drained Young’s Modulus of 5000 MPa was adopted for the rock surface. All DEFPIG and GARP analyses considered an average clay Poisson’s ratio of 0.4. The water level was initially assumed to be at the ground surface, being lowered to an average level of 1.5 m below ground surface to take into consideration excavation effects (to be described below). This was based on possible range of values adopted during excavation and dewatering at this site – the real values are unknown to the authors;
- Pile Characteristics and Location: The elastic modulus of the pile was considered as constant during GARP analyses, being obtained via DEFPIG analysis with the assumed soil profile and Young’s moduli, and with the given pile characteristics. The 104 composite floating piles were considered to be vertical (and uniform) with a constant diameter of 0.3 m, and length of 26 m. They were also considered to be mainly of timber, with an assumed Young’s Modulus of 18000 MPa and Poisson’s ratio of 0.2. In all GARP analyses the piles were assumed to apply a uniform pressure to square elements of similar area (to the pile section) in the raft;
- Raft Characteristics and Location: The Young’s Modulus of the raft was assumed to be 25000 MPa, its Poisson’s ratio to be 0.2, and its thickness to be 0.4 m. The base of the raft was assumed to be at the top level of the piles, with full contact with the underlying soil. An approximate dimension of 75 x 12 m (area ≈ 1000 m²) was adopted in the analyses, with uniform pressures of 61.5, 35 and 30 kPa (parametric analyses) evenly distributed around the top surface of the raft – again, to be explained soon;
- Bearing Capacity of Pile and Raft: The long term bearing capacity of the piles was estimated and used, since the final, total settlement was desired. The point bearing capacity was calculated via a traditional effective stress approach. A drained friction angle of 25° was assumed for the clay. The shaft resistance was calculated via the “Beta” method for drained soils, using the same angle of 25° and assuming a coefficient of lateral pressure K_0 of 0.8 ($OCR > 1$). These are typical values found in the literature for marine clays (assuming that variations can possibly happen). The total depth of the piles was taken into consideration for the calculation of the vertical stress levels, assuming a bulk unit weight of 16.5 kN/m³ for the soil layer. The group efficiency was estimated via the Poulos & Davis (1980) equation, which considers the sum of the ultimate capacities of individual piles and the ultimate load capacity of the “block” containing piles

and soil. An efficiency very close to 1.0 was calculated, and a unit value was therefore assumed. A drained bearing capacity was also calculated for the raft, adopting the Terzaghi (1943) equation again using a friction angle of 25° for the clay;

- Interaction Factors: These were obtained via the DEFPIG analysis, and used within GARP for pile/pile and pile/raft settlement interactions – given the lack of pile load tests on the site (none was found or apparently published). These interactions were limited to a horizontal spacing equal to the total length of the pile, *i.e.* 26 m and were assumed to be zero for greater spacings. The raft/raft and raft/pile interactions were obtained via the Boussinesq elastic equations, assuming an elastic continuum model and making approximate allowance for soil layering (*E*'s variable);
- Pile and Raft Discretization: A non-symmetrical mesh with 940 nodes and 855 elements was assumed for the raft in the GARP analyses, as depicted in Fig. 3. The piles were introduced in the nodes (crossings) of this same figure, following the real disposition depicted in Fig. 1. In the DEFPIG analysis each pile was divided into 52 elements, each 0.5 m in length;
- Initial Numerical Analysis: A drained Young's Modulus of 8200 kPa and 15000 kPa was adopted for the clay. A calculated raft pressure of 61.5 kPa was adopted for the long term settlement analysis – Cases 1 and 4. These cases were followed by another analysis with a variable Young Modulus, keeping the same raft pressure – Case 6;
- Parametric Analysis: Six cases were analyzed according to Table 1. The soil Young's Modulus was considered as constant with depth (8200 and 15000 kPa – cases 1 to 5) with depth or variable (see table – case 6). The pressure on top of the raft was considered as 61.5 kPa uniformly distributed, in accordance to the published total load of the house (61.5 MN) and raft area of around 997 m² in accordance to cases 1, 4 and 6. The final net effective pressures of 30 and 35 kPa, adopted in cases 2, 3 and 5, were calculated by considering the excavation process;

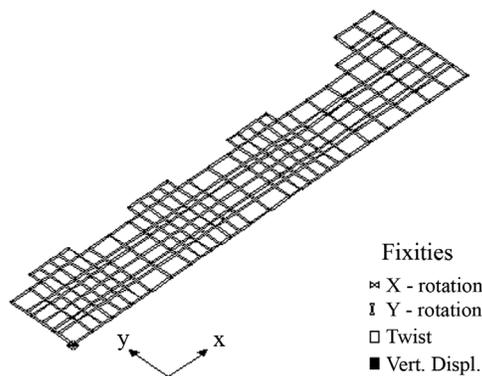


Figure 3 - Discretization of the finite element mesh of the foundation (raft and piles).

Table 1 - Parametric analyses adopted in this manuscript.

Case	<i>E</i> 's (kPa)	ΔP raft (kPa)	Raft position
1	8200	61.5	Surface
2	8200	35	Buried
3	8200	30	Buried
4	15000	61.5	Surface
5	15000	30	Buried
6	Variable*	61.5	Surface

**E*'s varying from 6600 kPa (top) to 11800 kPa (bottom of layer).

- Excavation sequence: By analyzing the accessed information of the original Hansbo (1993) paper, it appears that the raft was not cast on the deposit's surface, but rather buried on the subsoil. It was then estimated to have been constructed within an excavation of 2.5 m with the final water table at 1.5 m below ground surface. A simplified approach (hand calculation) was carried out to evaluate the net final effective pressure at raft level (as stated before, around 30 to 35 kPa). This approach adopted the same qualitative soil behavior as numerically found by Hsi & Small (1992) when simulating a 1-D excavation in a poro-elastic material. It was considered that the raft load was applied immediately after the soil excavation, *i.e.*, before any pore pressure change from negative to positive values – which is obviously another simplified assumption.

5. Results and Discussions

5.1. Overall results

The results of the numerical analyses were compared in terms of the extreme (maximum and minimum) values of settlement and moment (in both x and y directions). The load sharing between the piles and the raft was also computed and compared. These results are presented in Table 2, while Figs. 4 to 6 depict the contours of vertical settlement respectively obtained for Cases 1, 4 and 2. The discussion on the results comes in an itemized manner after that.

The contour legend represents the limits (in meters) for the obtained settlement results. For instance, in Fig. 6 the black (central) region represents the area of the raft with derived settlements between 4.5 and 5 x 10⁻² m, *i.e.*, 4.5 to 5 cm.

The comparison in terms of absolute extreme values is useful to indicate general behavioral tendencies from the different input parameters adopted with this particular piled raft foundation.

Hence, some general observations can be drawn from the results of Table 2 and from Figs. 4 to 6:

- By increasing the Young's Modulus of the soil, while keeping all other variables constant, there is a tendency for both (max./min.) settlements and moments to de-

Table 2 - Settlement, moment and load sharing results from all the analyses.

Case	Settlement (cm)		Moments (kNm)				Load share (%)	
	max	min	Mx (max)	Mx (min)	My (max)	My (min)	Piles	Raft
1	8.3	3.0	128	-237	208	-113	75	25
2	4.7	1.7	73	-133	117	-63	75	25
3	4.1	1.5	62	-114	100	-54	75	25
4	5.3	1.9	100	-197	163	-107	66	34
5	2.6	0.9	49	-96	80	-52	66	34
6	7.4	2.6	129	-243	202	-118	77	23

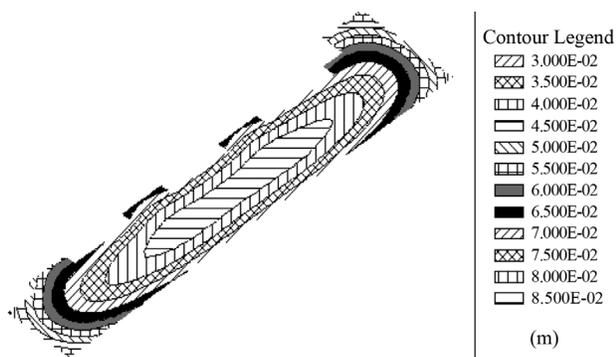


Figure 4 - Contours of vertical settlement (m) – CASE 1 – surface raft.

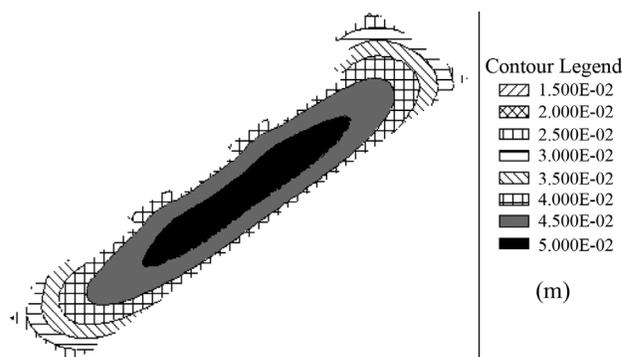


Figure 6 - Contours of vertical settlement (m) – CASE 2 – buried raft.

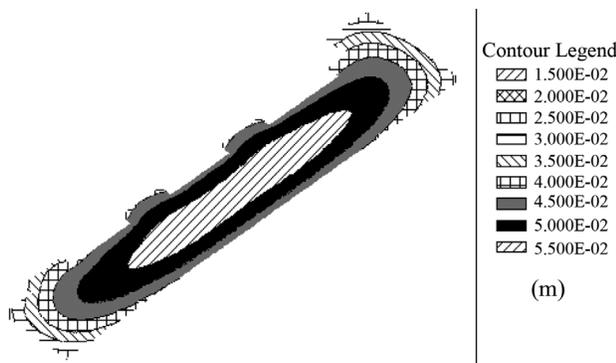


Figure 5 - Contours of vertical settlement (m) – CASE 4 – surface raft.

crease, as expected. There is also a slight tendency for the load carried by the raft to increase, reducing the load carried by the piles;

- For a variable $E's$ rather than a constant $E's$, there is a tendency for the settlement values to be intermediate between those obtained with a constant $E's$. Nevertheless, similar results for moments and load division were obtained for both Cases 1 and 6;
- By decreasing the distributed pressure on top of the raft, while keeping all other variables constant, there is a tendency for both (max./min.) settlements and moments to

decrease, again as expected. However, there was no variation in the load sharing between raft and piles;

- It is also noticed that similar contours of total settlement were obtained in Figs. 4 to 6 for each of the cases analyzed, although the magnitude of the settlements varied from one case to another. This indicates that all cases tended to develop similar patterns of settlement, albeit distinct values of input $E's$, raft position (buried or not) and raft pressure. Indeed, given the homogeneity of the subsoil, and linearity of loads and responses (structure and soil's modulus), such similarities were already anticipated.

In summary, the analyses demonstrated the important influence of the assumed drained Young's Modulus of the clay, and the distributed load, on the predicted values of settlement and moment. The Young's Modulus has also some influence on the total load sharing between raft and piles, but to a lesser extent than the influence on the settlement.

5.2. "Class A" analyses and the assessment of the excavation

It was mentioned before that, despite the fact that this particular case history has already been published elsewhere (and the final total settlements are supposedly known), some effort has been made to characterize the numerical analyses as truly "Class A" predictions. That means, to check the predictions against the (unknown during analy-

sis) measured values. Hence, Cases 1, 4 and 6 (initial numerical analysis with the raft at surface) were analyzed solely on the basis of the information provided by Van Impe (1999) in the international exercise, without referring to the Hansbo (1993) or Hansbo & Källström (1983) papers.

The predicted settlements, presented in Table 2, varied from about 5 to 8 cm (maximum) and about 2 to 3 cm (minimum). In fact, as noted before, these settlements were strongly related to the assumed drained modulus of the clay, and the other assumptions in terms of raft pressure and position adopted for the input parameters. By comparing the predicted results with those from Hansbo (1993), depicted in Fig. 7, it was noticed that they are somewhat different from the measured “real” published settlements, which ranged from 2.5 (min.) to 4.2 cm (max.). That means, the experimental values were well below the predicted values at class A prediction from Table 2, indicating that either the model did not accomplish the nuances of the rheological phenomena or the input elastic parameters were slightly lower (“softer”) than those from the real subsoil (or something else, as the actual stiffening effect of the basement beams on the overall displacement pattern).

In order to understand the possible reason for such discrepancies, the authors carefully reviewed the Hansbo (1993) paper. This extra exercise revealed that an excavation was probably carried out before the construction of the piled raft (as suspected by aforementioned comments). This excavation was not considered in the initial numerical analyses with Cases 1, 4 and 6, given the lack of detailed information about this particular case history. Indeed, the excavation process prior to the raft placement may have a large effect on the final settlement results, since it considerably changes the original stress state (see for instance Hsi & Small, 1992). According to Sales *et al.* (2010), the stress relief and preloading process that takes place during the excavation and casting of the foundation raft must be taken into account to properly simulate the

loading pattern, and hence to accurately forecast the settlements at working load.

In order to account for this effect, at least in a reasonable but simplified manner (as proposed by Ibáñez *et al.*, 2014), extra parametric analyses were made considering the excavation. The new assumption resulted in the final net effective pressures of 30 and 35 kPa below the raft, as adopted for Cases 2, 3 and 5 in which the raft was considered to be buried. Of course, in these particular cases, it is readily noticed that they consisted of “Class C” predictions for this particular exercise (as the authors already knew the “target” values), rather than “Class A” predictions as done before.

The new effective pressures were estimated by simple hand calculations where the effective vertical pressures below the raft were determined with the excavation effect on the groundwater pressure. That means, immediately after 2.5 m (1D) excavation the positive water pressure (with water table at ground surface) became negative in accordance to Hsi & Small (1992) advocated technique. Once the raft load is applied, by casting of the foundation, the water pressure changes again to a positive value. At this stage, it was assumed that two things took place simultaneously: The lowering of the water table from ground surface to 1.5 m below ground (dropped 1 m in height) and full dissipation of the excess pore pressures (positive excess in the previous step) to take into account long term effects. The final variation of net effective vertical pressures is simply the difference between initial and final values below the raft. Perhaps this procedure can be better visualized with the values of Table 3.

Within the context of the analyses carried out for Cases 2, 3 and 5, a reduction in the maximum settlement as high as 50% can be noticed in Table 2. It is also noticed that a variation on the effective Young’s Modulus was also tried out from cases 2, 3 to 5, in order to improve even more the predictions (again, a typical “Class C” analysis since the measured results were known in advance allowing the optimization of the numerical output). The important point to note, however, relates to the fact that even by knowing beforehand the results, the present authors were unable to accurately and definitively predict the settlement pattern presented by Hansbo (1993), as depicted in Fig. 7. See, for instance, the marked differences in the pattern of vertical settlement from Figs. 6 to 7.

Although Fig. 6 presents settlement values close to the right magnitude, they were predicted to vary in a concentric “dishing” manner within the raft, which differs from the measured (real) pattern depicted in Fig. 7. This figure portrays higher settlements at the left side of the house, which could be due to some possible factors, as follows: uneven distribution of raft pressures (due to concentrated loading from existing columns), a variable clay layer profile and/or the stiffening effect of the foundation beams (in what is called as a “soil-superstructure effect”). Neither

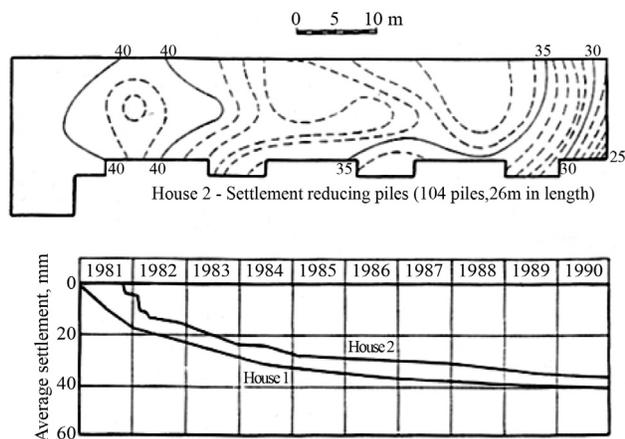


Figure 7 - Measured settlement contours in House 2 (modified after Hansbo, 1993).

Table 3 - Variation of pore, effective and total vertical pressures underneath the raft.

Condition	Pore pressure (kPa)	Eff. vertical pressure (kPa)	Total (*) vertical pressure (kPa)
Initial state before excavation	25	16.25	41.25
Immediately after 2.5 m excavation with GWT at surface	-16.25 (**)	16.25	0.0
Application of raft load and molding	—	—	61.5
After curing, GWT at surface	45.25	16.25	61.5
GWT at 1.5 m below surface and full consolidation	10	51.5	61.5
Δ Effective Net Vertical Pressure =		$51.5 - 16.25 \approx 35$ kPa	

*Considering a total unit weight of around 16.5 kN/m^3 .

**Considering Hsi & Small (1992) approach.

conditions were considered herein, given the lack of detailed information on these parameters, as well as software capabilities.

In summary, the main observation of the final series of analyses is that the problem lacked a great deal of important information, even for a proper “Class C” prediction (see previous comment related to cases 2, 3 and 5). Besides the shortcomings of these analyses, the present exercise was valuable in showing possible deficiencies in standard numerical design analyses, and the importance that the excavation effect, among others, has in fine tuning the settlement results. It has shown that the detailed knowledge of some input variables is essential for the proper numerical simulation of real engineering projects, and, besides all, that some extra external influential variables (nowadays considered as circumstantial aspects of the problem) should be taken into account in future numerical predictions of piled rafts.

Indeed, recently in Brazil (at its latest national geotechnical conference of 2016 – XVIII COBRAMSEG) colleagues from the geotechnical and structural area have agreed, in a special session of the event (soil-superstructure effects), that future analyses must deal somehow with this aspect (as done in a simplified manner by Cunha & Cambar, 2011), either in terms of the building structural modelling or in terms of the foundation discretization. Unfortunately, the designer is still far from reaching an agreement on how to do that in practice, and with what tools (and parameters). As a final piece of information given in this same conference, some “educated” accounts given by colleagues on the budgetary aspects of the design foresee an increase of 0.04% in the final price of the elaboration of the geotechnical design, *i.e.*, this component of the project would increase from around 0.20% of the total budget of the building construction to around 0.24%. Is the price increase worthy of the benefits of a better understanding of the whole superstructure – foundation system (hence more accurate analyses)? The future will hopefully provide answer.

6. Conclusions

The results of the present exercise highlight the fact that in practice it is extremely important to understand all input parameters which are required in the design of both piled rafts and standard (conventional) groups of piles. This is so regardless of the “accuracy” and capabilities of the numerical program in question.

This contribution has shown that it is not possible to precisely predict the behavior of piled rafts and group of piles, in both “Class A and C” analyses, without a full understanding of the problem and knowledge of its important input parameters, such as the raft geometry and load distribution (magnitude, pattern, variability with time), the excavation depth and sequence, the seasonal variability of the water level, the soil profile (depth, variability, layering), and, finally, without a comprehensive laboratory or in situ testing program. It has also allowed a clear perception of the possible influence of the lack of information of some of the above variables in the final numerical assessment of a published piled raft case history, particularly the excavation process (simulated in a simplified manner) and the soil-superstructure stiffening influence (not taken into account).

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References

- Burland, J.B. (1995). Piles as settlement reducers. Keynote Address, 18th. Italian Conf. on Soil Mechanics, Pavia, pp. 21-34.
- Clancy, P. & Randolph, M.F. (1996). Simple design tools for piled raft foundations. *Géotechnique*, 46(2):313-328.
- Cunha, R.P. & Cambar, T.T. (2011). Numerical and experimental assessment of the soil-structure interaction effect of a building in the Brazilian central area. Proc. 14th. Pan-American Conf. on soil Mech. and Geot. Engineering, Toronto, pp. 1-7, CD-ROM.
- Cunha, R.P. & Sales, M.M. (1998). Field load tests of piled footings founded on a tropical porous clay. Proc. 3rd Inter. Geot. Seminar Deep Foundation on Bored and Auger Piles, Ghent, pp. 433-438.
- Cunha, R.P.; Poulos, H.G. & Small, J.C. (2001). Investigation of design alternatives for a piled raft case history. *ASCE Journal of Geotechnical and Geoenvironmental Engineering*, 127(8):635-641.
- Cunha, R.P.; Small, J.C. & Poulos, H.G. (2000a). "Class C" analysis of a piled raft case history in Gothenburg, Sweden. Year 2000 Geotechnics – Geotechnical Engineering Conference, Bangkok, v. 1, pp. 271-280.
- Cunha, R.P.; Small, J.C. & Poulos, H.G. (2000b). Parametric analysis of a piled raft case history in Uppsala, Sweden. Fourth Brazilian Seminar of Special Foundation Engineering and Geotechnics-SEFE IV, São Paulo, v. 2, pp. 381-390.
- Hansbo, S. (1993). Interaction problems related to the installation of pile groups. Proc. 2nd Inter. Geot. Seminar Deep Foundation on Bored and Auger Piles, Ghent, pp. 59-66.
- Hansbo, S. & Källström, R. (1983). A case study of two alternative foundation principles. *Väg-och Vattenbyggarren*, 7(8):23-27.
- Hsi, J.P. & Small, J.C. (1992). Simulation of excavation in a poro-elastic material. *Int. Journal for Numerical and Analytical Methods in Geomechanics*, 16(1):25-43.
- Ibáñez Mora, L.O.; Cunha, R.P. & Fernández, D.H. (2014). Analysis of foundations on compensated piled rafts. XVII Cong. Bras. Mec. Solos e Eng. Geotécnica – COBRAMSEG 2014, Goiânia, pp. 1-7. CD-ROM. (In Portuguese).
- Mandolini, A. & Viggiani, C. (1997). Settlement of piled foundations. *Geotechnique*, (47)4:791-816.
- O'Neill, M.W.; Caputo, V.; De Cock, F.; Hartikainen, J. & Mets, M. (1996). Case histories of pile-supported rafts. Report for ISSMFE TC18, Univ. of Houston, Texas.
- Ottaviani, M. (1975). Three-dimensional finite element analysis of vertically loaded pile groups. *Géotechnique*, 25(2):159-174.
- Poulos, H.G. (1990). *Defpиг User's Guide*. Centre for Geotechnical Research, University of Sydney, 55 p.
- Poulos, H.G. (1991). *Foundation Economy Via Piled-Raft Systems*. Piletalk International, Kuala Lumpur, pp. 97-106.
- Poulos, H.G. (1998). The Pile-Enhanced Raft - An Economical Foundation System. Keynote Lecture at XI Brazilian Congress on Soil Mechanics and Geotechnical Engineering, Brasília, v. 4, pp. 27-43.
- Poulos, H.G. & Davis, E.H. (1980). *Pile Foundation Analysis and Design*. Robert E. Krieger Publishing Co. Sydney, 397 p.
- Poulos, H.G. & Small, J. C. (1998). *Garp User's Manual*. Coffey Partners International Pty Ltd. Sydney, 23 p.
- Randolph, M. (1994). Design methods for pile groups and piled rafts. XIII Int. Conf. on Soil Mechanics and Found. Engineering, New Dehli, v. 5, pp. 61-82.
- Sales, M.M.; Small, J.C. & Poulos, H.G. (2010). Compensated piled rafts in clays soils: behavior, measurements and predictions. *Canadian Geotechnical Journal*, 47(3):327-345.
- Ta, L.D. & Small, J.C. (1996). Analysis of piled raft systems in layered soils. *Int. Journal for Numerical and Analytical Methods in Geomechanics*, 20(1):57-72.
- Terzaghi, K. (1943). *Theoretical Soil Mechanics*. New York, John Wiley and Sons, 510 p.
- Van Impe, W.F. (1999). International exercise on piled rafts – Sweden Examples. International Society of Soil Mechanics and Geotechnical Engineering TC-18 Committee. WVI/HDC/WIV.3.5 Report – Gent University.