CASE STUDIES FOR PILED RAFTS ON CLAY

H S W Chow[1] and J C Small[2]
[1]Coffey Geotechnics Pty Ltd. [2]The University of Sydney, NSW 2006

ABSTRACT

Piled rafts have proved to be an effective way of improving the overall performance of a foundation. In the case of structures built on clay, a raft foundation alone may result in excessive settlement. A piled raft foundation is a solution in which the piles provide localised support in heavily loaded regions or areas where deflection is excessive and results in reducing the overall and differential settlements as well as tilting of the foundation. Case histories for piled-rafts foundation on clay will be presented in this paper. The foundations have been studied using a finite layer method for the analysis of a horizontal layered soil and a finite element method for the analysis of the raft and piles. The analysis takes into account the complex soil-structure interactions which govern the behaviour of the piled raft. Case studies of piled rafts on clay will be examined and the results will be compared with the *in situ* measurements and other numerical results. Comparisons are made in terms of load distribution among piles and the overall and differential settlements.

1 INTRODUCTION

Conventional piled foundation design neglects the contribution of the raft to the overall performance of the foundation. However, in practice the raft can carry a significant proportion of the total structural load. Piled rafts are composite structures comprised of the piles, raft and soil which take into account the interactions between the rafts, piles and soil in the design. The loads acting on the foundation are transferred to the soil through the raft and the piles. These loads are shared between the raft and piles with the majority of the load being designed to be carried by the piles. The main purpose of the piles is to improve the bearing capacity and to reduce both the overall and differential settlements and tilting of the foundation. Over the past decades, extensive research work on piled raft foundations has been presented, aimed at improving the accuracy in the prediction of the behaviour of piled rafts (Poulos, 1994; Ta and Small, 1996, Katzenbach and Reul, 1997; Reul and Randolph, 2003 and 2004).

The scope of this paper is to study some case histories for foundations on compressible soil materials. The results are compared with *in situ* measurements and predictions obtained by other numerical methods.

2 NUMERICAL MODELLING OF PILED RAFTS

A computer program APRILS has been used for the analysis of the piled rafts studied in this paper. APRILS employs the finite layer technique for the analysis of the layered soil foundation and the finite element technique for the analysis of the raft and piles. The raft is divided into a number of 8 noded isoparametric rectangular elements and the base of the raft is assumed to be perfectly rough. The piles are rigidly attached to the raft at the nodes as shown in Figure 1. Each pile is divided into a series of two noded beam elements. The soil is divided into horizontal layers corresponding to the number of elements in the pile.

The analysis involves the separation of the foundation into an isolated piled raft and the layered soil as shown in Figure 2. The raft is subjected to external and interface forces (contact and shear stresses) that exist between the raft and soil. The contact stresses between the raft and soil are represented by rectangular blocks of uniform pressure and the shear stresses are represented by a series of uniform rectangular shear stresses. The pile group is subjected to interface forces between the pile and soil. The loads acting on the piles are transferred from the piles to the soil through shear and lateral earth pressure along the pile shafts and the normal contact and shear stresses at the pile base. The shear and lateral earth pressures along the pile shaft are approximated as a series of ring loads applied at the soil interfaces in both the vertical and horizontal directions. The stresses at the pile base are approximated as a uniform circular load having the same diameter as the pile base in both vertical and horizontal directions.

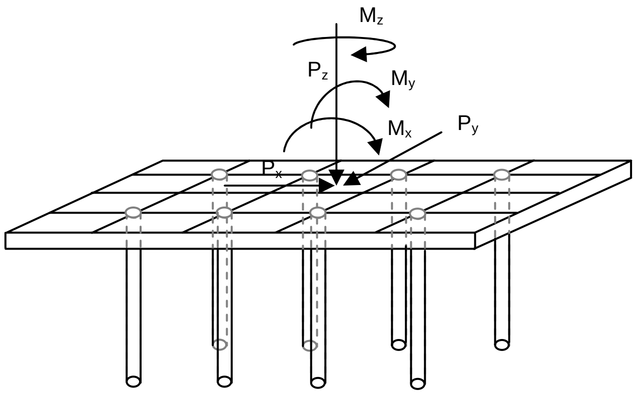
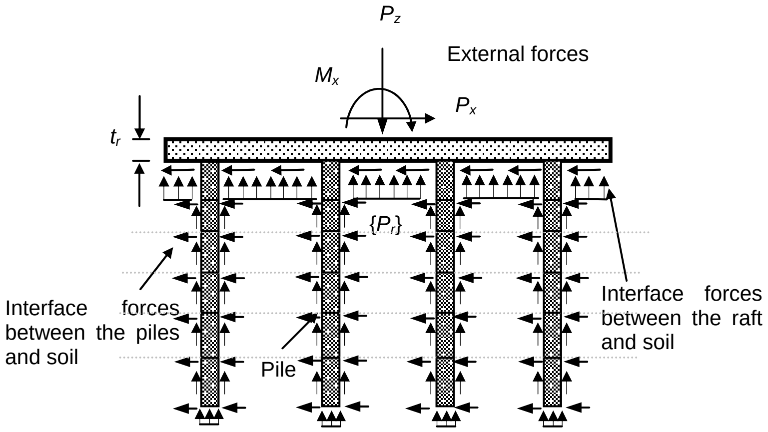


Figure 1: Attachment of Piles to the Raft



Interface forces transferred from piled raft to the soil

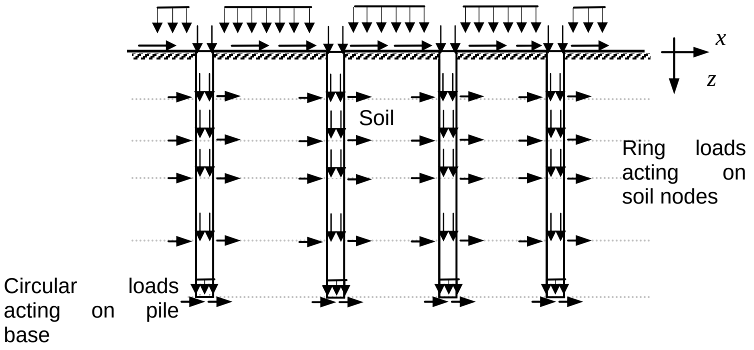


Figure 2: Forces acting on the Piled Raft

Complex soil-structure interaction has been considered in the analysis by the application of a unit ring load at the soil interface or a uniform pressure at the soil surface. By using the finite layer technique, the deflections of the soil along the pile shaft or soil surface due to the applied load can be computed. These deflections will form the influence matrix for the soil and can then be used for the determination of the displacement of the piled raft foundation. The method has been more fully explained in Chow and Small (2005a and b).

3 CASE HISTORIES

3.1 CASE 1 - STONEBRIDGE PARK, LONDON, UK

A 16-storey apartment building at Stonebridge Park in London, England constructed on London Clay has been studied by Cooke *et al*. (1981) and Horikoshi and Randolph (1995). The building is 42.8 m high and is rectangular in plan. A piled raft was adopted as the foundation for the building due to the excessive settlement predicted for an unpiled raft foundation. The piles were designed to carry all the structural load.

The foundation consists of a 0.9 m thick rectangular raft that is 19.2 m x 43.3 m in plan and is supported by 351 bored piles with a diameter of 0.45 m and a length of 13 m. The piles were installed on a square grid with a centre-to-centre spacing of 1.6 m. The foundation was subjected to a total load of 155.6 MN which included the dead and live loads as well as the weight of the raft. The symmetrical foundation allowed the foundation instrumentation to be confined to one quadrant which includes eleven contact pressure cells underneath the raft, one magnet extensometer with points located from the surface to a depth of 35 m below the raft (to monitor soil movements) and eight instrumented piles as shown in Figure 3.

The geological profile consists of London clay with a depth of at least 25 m from the ground surface. The undrained shear strength of the London Clay varied linearly from 100 kPa at the ground surface to 190 kPa at the pile toe and then to 260 kPa at a depth of 25 m. Horikoshi and Randolph (1995) adopted the soil shear modulus correlation:

$$G_s = 200 s_u \text{ (kPa)} \qquad \textbf{(1)}$$

where $s_u = 100 + 7.2\,z$ (kPa) and z is the depth below the ground surface in metres. The Poisson’s ratio for the soil was taken as 0.1.

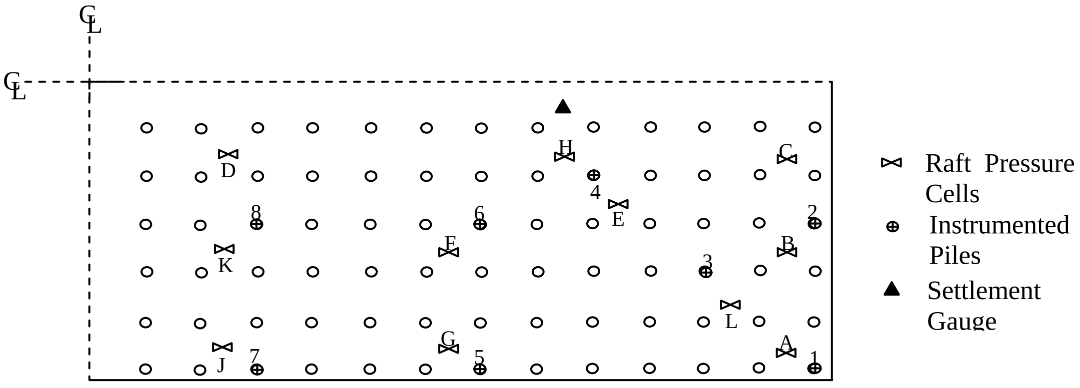


Figure 3: Instrumentation Quadrant for Stonebridge Park Apartment Building (Cooke *et al.,* 1981).

Program APRILS was used to examine the behaviour of the piled raft foundation. Figure 4 shows the finite element mesh of the entire piled raft used in the analysis. The piles are attached to the raft at the nodes and each pile is divided into 9 elements. The raft is subjected to a uniform load of 188 kPa. Figure 5 shows the settlement contours for the foundation from the APRILS analysis. Based on the extensometer measurements the average settlement on the perimeter is about 13 mm with a differential settlement of 4 mm at the end of construction. Figure 6 shows the predicted settlement along the perimeter of the raft which is in good agreement with the measured settlement.

From the field measurement, the load carried by the corner piles was approximately two times the load carried by the inner piles. The shaft friction developed along the inner piles was about 35% of a pile at the corner. From the APRILS analysis, the corner and edge piles were carrying about the same load and the load carried by the inner piles was about 20% less than the corner and edge piles. Figure 7 shows the comparison of the average measured and predicted pile loads. There is a good agreement between average predicted and measured pile load for the edge piles. However, the predicted loads for the corner and inner piles are about 20% different from the measurements. Such a difference could be due to the assumption of a uniform load applied to the raft in the APRILS analysis.

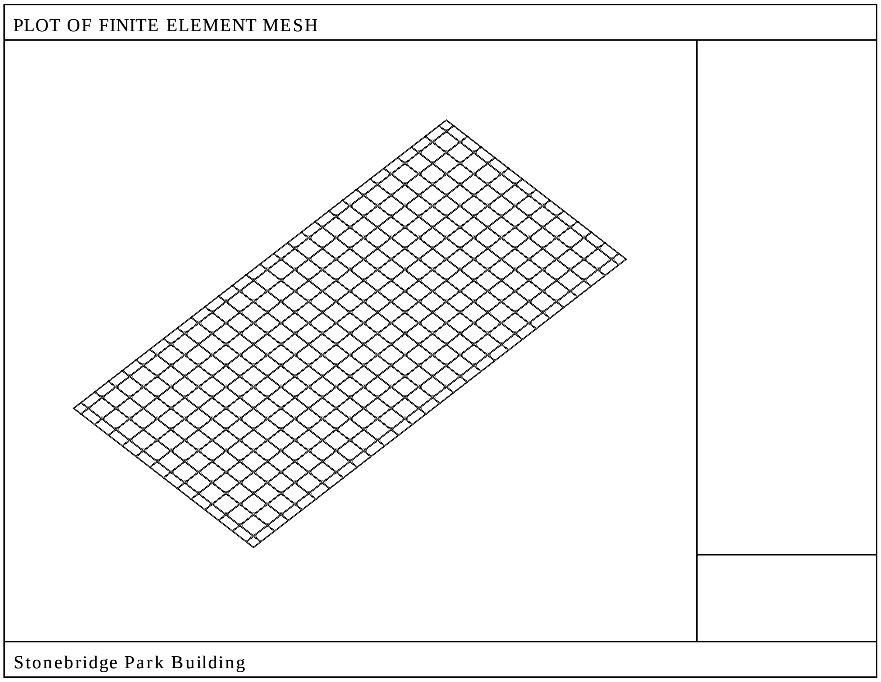


Figure 4: Mesh of Piled Raft for Stonebridge Park Building .

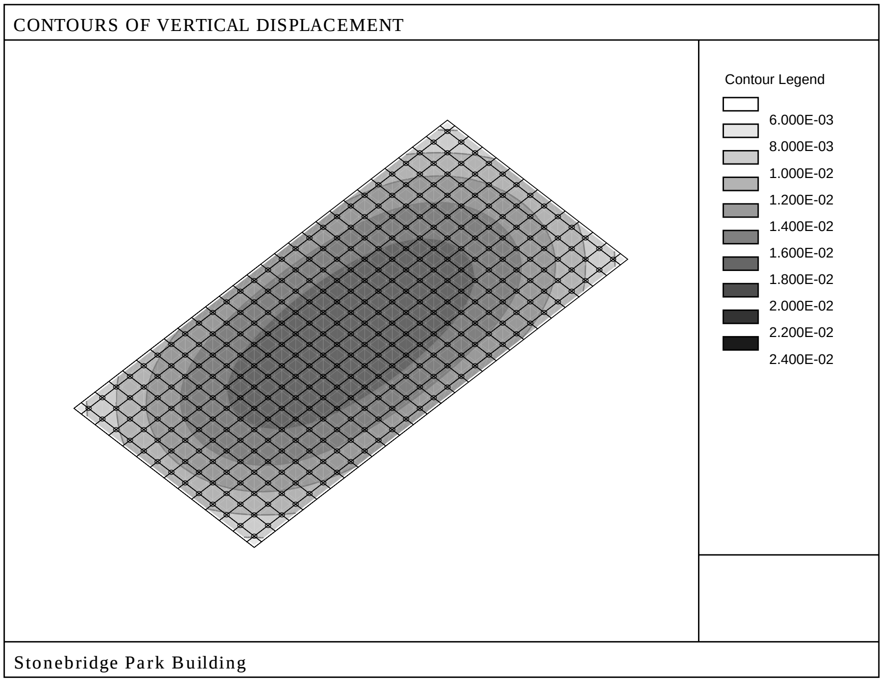


Figure 5: Settlement Contours for Piled Raft of Stonebridge Park Building.

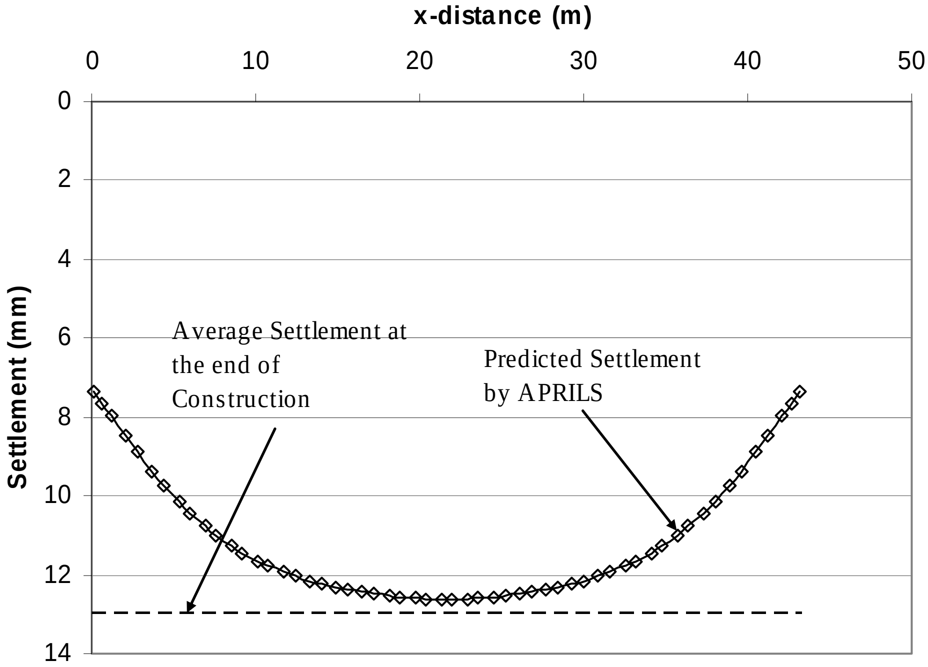


Figure 6: Comparison of Measured and Predicted Settlement along the Perimeter of the Piled Raft.

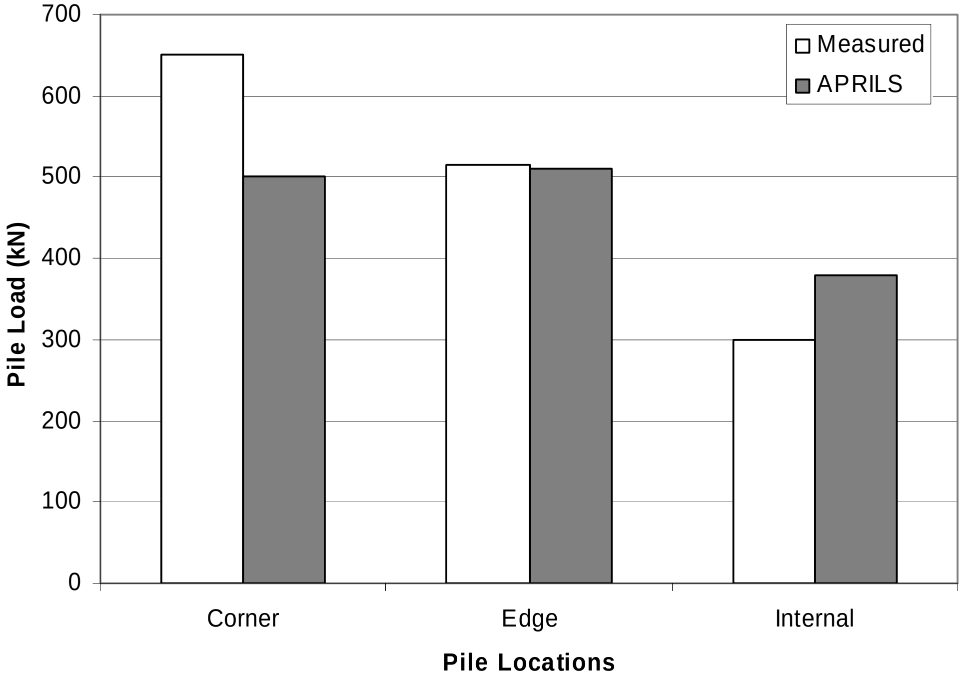


Figure 7: Comparison of Measured and Predicted Pile Loads at Different Locations.

3.2 CASE 2 – APARTMENT BUILDING AT UPPSALA

An apartment building in Uppsala, Sweden constructed on marine and lacustrine clay has been studied by Jendeby (1986) and El-Moussallamy (2000). The apartment has four-storeys with a basement and the plan area is approximately 532 m^2. A creep-piled raft was adopted as the foundation for the apartment block.

The foundation consisted of a raft supported by 48 composite piles. The raft has a dimension of 38 m x 14 m in plan and a thickness of approximately 0.4 m. The composite piles consist of a 0.3 m diameter concrete section for the top 7 m spliced with an 18 m long timber pile. The diameter of the timber piles is assumed to be 0.3 m at the point of the splice and then reduce with depth. The piles are generally located along the basement walls as shown in Figure 8. The foundation is subjected to a total vertical load of 30.4 MN.

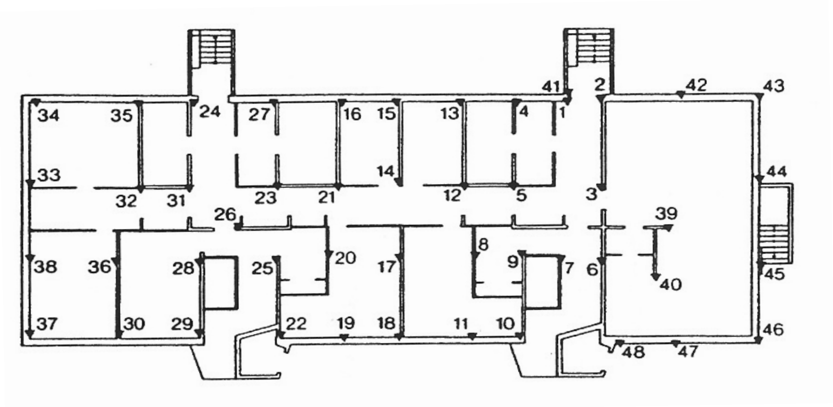


Figure 8: Locations of Piles for the Building, Uppsala (Jendeby, 1986).

The geological profile consists of soft marine clay with a thickness of up to 15 m underlain by lacustrine clay with a maximum thickness of 15 m. The thicknesses of each layer varies within the footprint of the building. Field tests including oedometer tests and vane tests have been carried out to determine the geotechnical parameters for the clay layers. The undrained shear strength is about 30 kPa for both clay layers. Based on the oedometer results, the preconsolidation pressure in the marine clay ranged from 20 kPa to 50 kPa, while the lacustrine clay is observed to be normally consolidated. Figure 9 shows the geotechnical characteristics of the soil profile.

The foundation was instrumented with different types of devices including 12 pile load cells, 10 contact pressuire cells, 3 bellows-hose settlement gauges and pore pressure gauges at 5 m intervals up to a depth of 35 m. Figure 10 shows the locations of instruments for the entire foundation.

In the design of a creep-piled raft foundation, the bearing capacity of the soil must be sufficient to support the building and the purpose of the additional piles is to reduce settlement. A creep pile is designed to carry a load nearly equal to the maximum pile resistance calculated from the long-term shear strength of the soil (Jendeby, 1986).

El-Moussallamy (2000) conducted an analysis by adopting the geotechnical parameters summarised in Table 1. The modulus of the clay was determined by equation **(2):**

$$E = 2 + 0.2z \qquad \text{(MPa)} \tag{2}$$

where z is the depth of soil below the base of the raft in metres. The modulus of the pile is determined from the weighted average of the modulus of concrete and timber. Table 1 summarises the geotechnical parameters for the piled raft.

Table 1: Parameters used for the piled raft design

Material	Clay	Piles		Raft
		Concrete	Timber	
Modulus (MPa)	E = 2 + 0.2 z	30,000	5,000	30,000
		Equivalent E = 10,000		

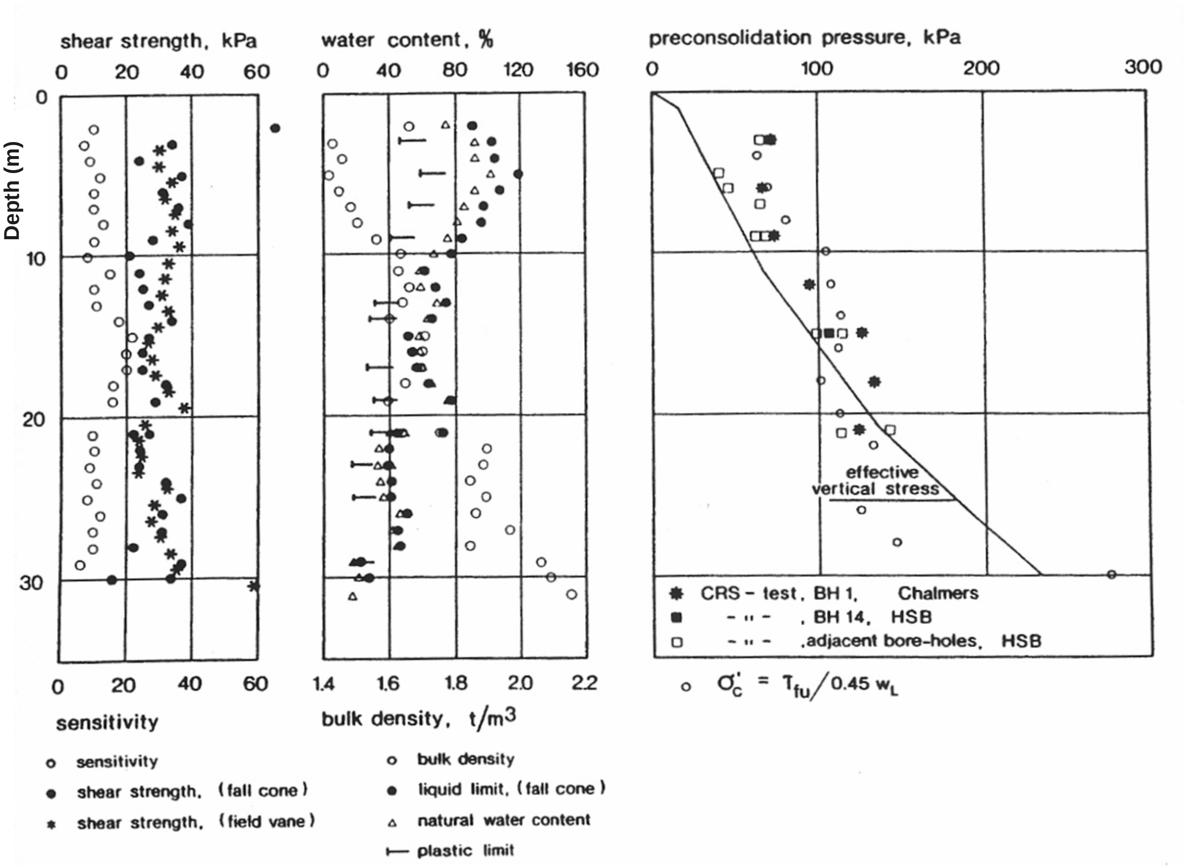


Figure 9: Geotechnical Characteristics at Uppsala Building Site (Jendeby, 1986)

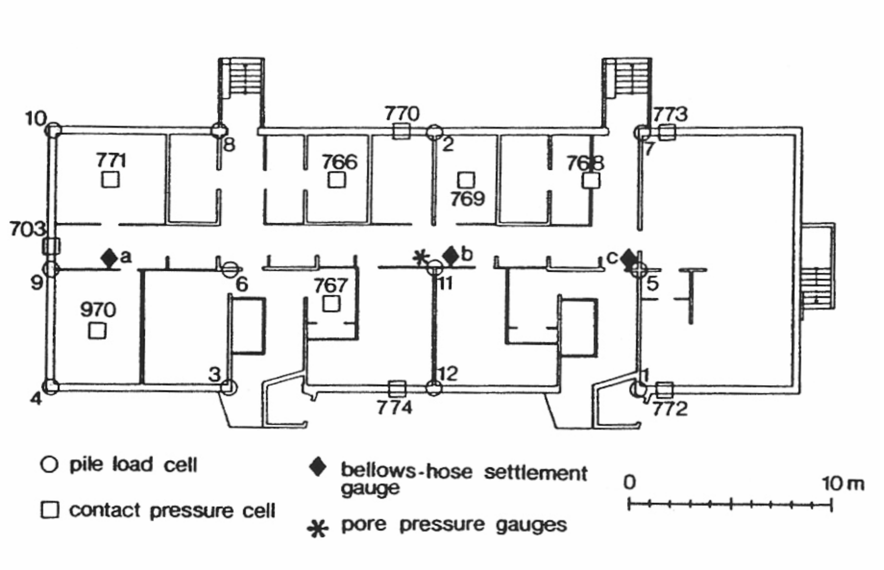


Figure 10: Locations of Instrumentation for the Entire Foundation

Program APRILS has been used to predict the settlement of the foundation. A uniform load of 57 kN/m^2 was applied to the raft which is equivalent to the total applied load of 30.4 MN. The computed settlement along the centre line of the raft is shown in Figure 11 and compared with the measured values at different settlement gauges locations as shown in Figure 10. The maximum settlement is about 52 mm which is about 2 mm larger than the measured settlement. Figure 12 shows the settlement contours of the raft and it is observed that higher settlement occurred at the central region of the raft.

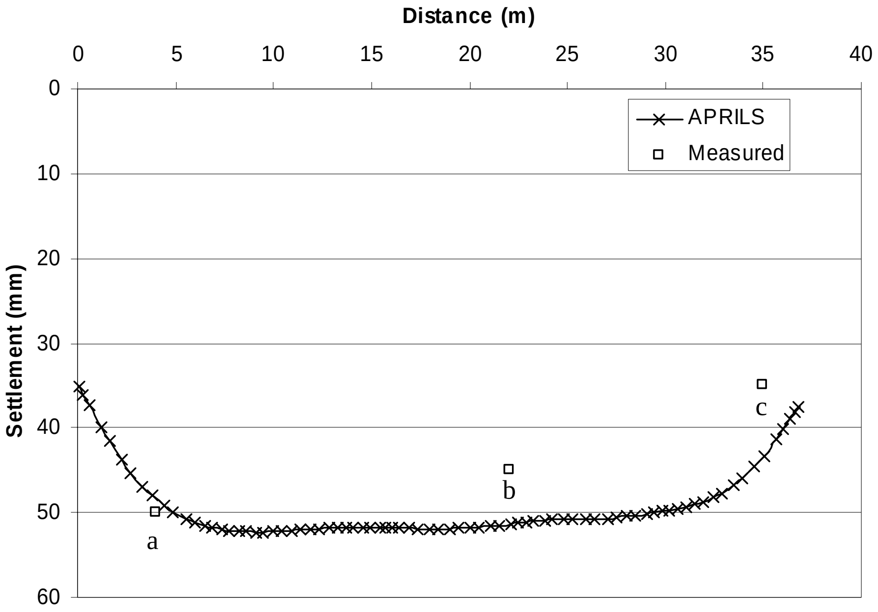


Figure 11: Settlement along the Centre Line of the Raft.

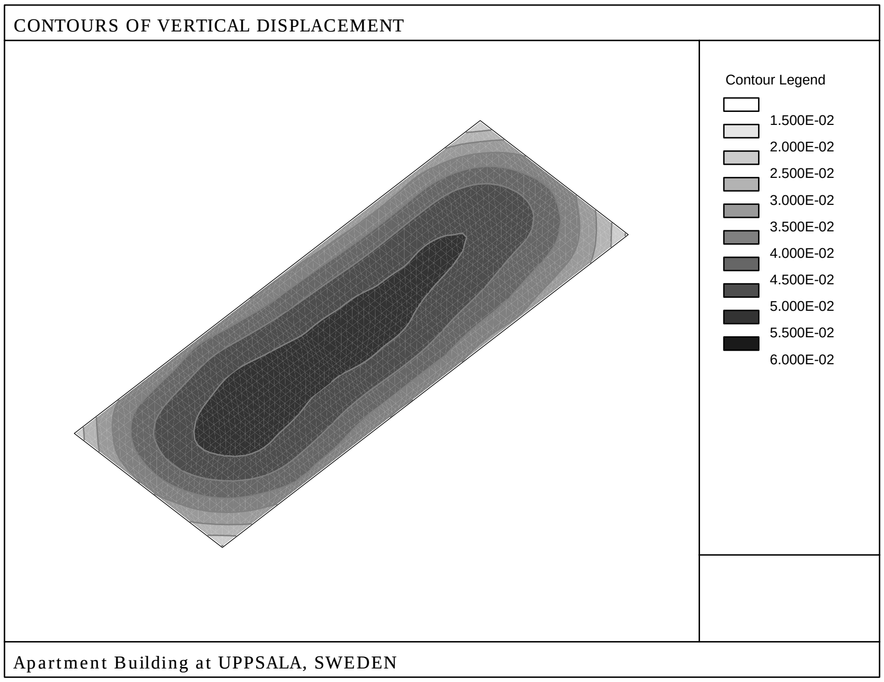


Figure 12: Settlement Contours of Raft.

The distribution of load along the piles at different locations is shown in Figure 13. The corner piles are predicted to carry the least load among the edge and centre piles and the centre piles carried the maximum loads due to the high flexibility of the raft. Based on the APRILS analysis, the load carried by the piles is about 72% of the structural load which is in contrast to the field measurements, which indicated that the load carried by the raft is higher than the piles. A redistribution of loading between the raft and piles was observed due to the changes in soil structures during the freezing and thawing periods (Jendeby, 1986). The raft carried more load when the soil was frozen, as the soil thawed, the load carried by the raft was shifted to the piles.

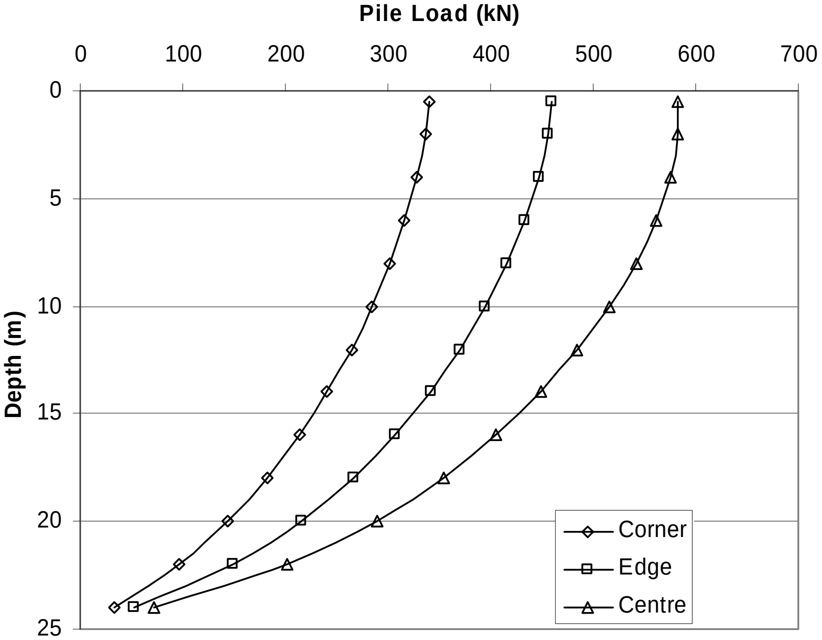


Figure 13: Distribution of Load along the Piles at Different Locations.

3.3 CASE 3 – TWO STOREY COMMERICAL BUILDING

A two storey commerical building was constructed on a deposit of clay with interbedded sand layers. The building has two storeys with a basement. The design of the foundation had to satisfy the design criteria of a maximum allowable settlement of 50 mm. A piled raft was adopted as the foundation for the building with foundation settlement as the major concern in the design.

The foundation consists of a raft supported by a total of 42 piles of which 36 piles have a length of 9 m and 6 piles have a length of 12 m. All of the piles have a diameter of 0.6 m. The long piles are used to support loadings from columns and the building core and short piles are used to support loadings from walls. The raft is L-shaped in plan with the dimensions shown in Figure 14 and has a thickness of 0.3 m. A total load of 45,800 kN was applied to the foundation.

The geological profile consists of stiff silt and clay layers interbedded with layers of sand and the bedrock level was inferred at a depth of 25.5 m below the surface. Table 2 summarises the geotechnical model and parameters adopted for the design. The moduli of the soil layers vary from 15 MPa to 75 MPa. The moduli of piles and raft were taken as 30,000 MPa.

The behaviour of the piled raft was examined by both program APRILS and the piled raft program GARP (Poulos, 1994). GARP employs the boundary element method for the computation of the interaction between piles or raft and piles. In APRILS, the piles are assumed to have an elastic behaviour, but in GARP the piles are assumed to have a non-linear load deflection behaviour. The stiffness of the basement wall has been taken into account in predicting the raft settlement by using stiff raft elements with a thickness of 0.6 m at the location of the basement wall. Figure 15 shows the finite element mesh of the raft with stiff elements to model the basement wall for both analyses.

Table 2: Adopted Geotechnical Model and Parameters

Depth (m)	Soil Material	Modulus, E (MPa)	Poisson's Ratio, ν
0 – 3	Silty Sand and Sandy Clay	15	0.3
3 – 4.5	Sand	75	0.25
4.5 – 9	Silt and Clay	15	0.3
9 – 10	Sand	75	0.25
10 – 14.5	Silt and Clay	15	0.3
14.5 – 16	Sand	75	0.3
16 – 17	Sand	25	0.25
17 – 17.5	Sand	50	0.25
17.5 – 20	Silt and Clay	22	0.25
20 – 20.5	Sand	75	0.3
20.5 – 25.5	Silty and Clay	30	0.25

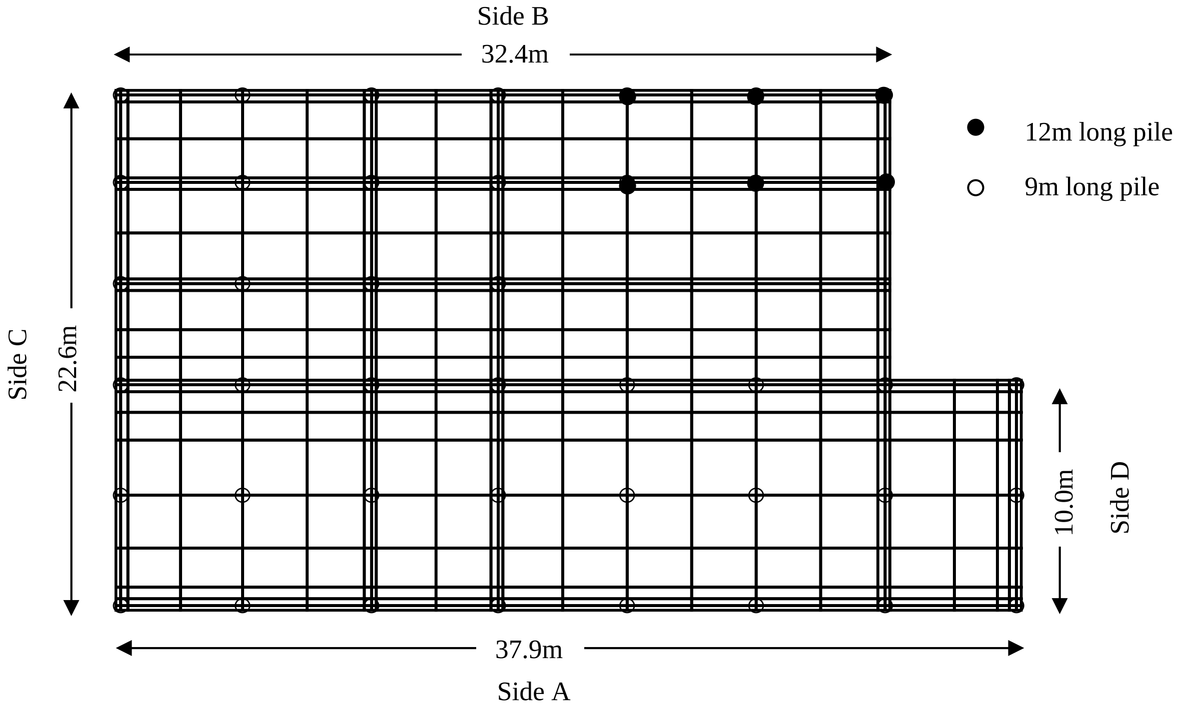


Figure 14: Dimensions of Raft for the Building.

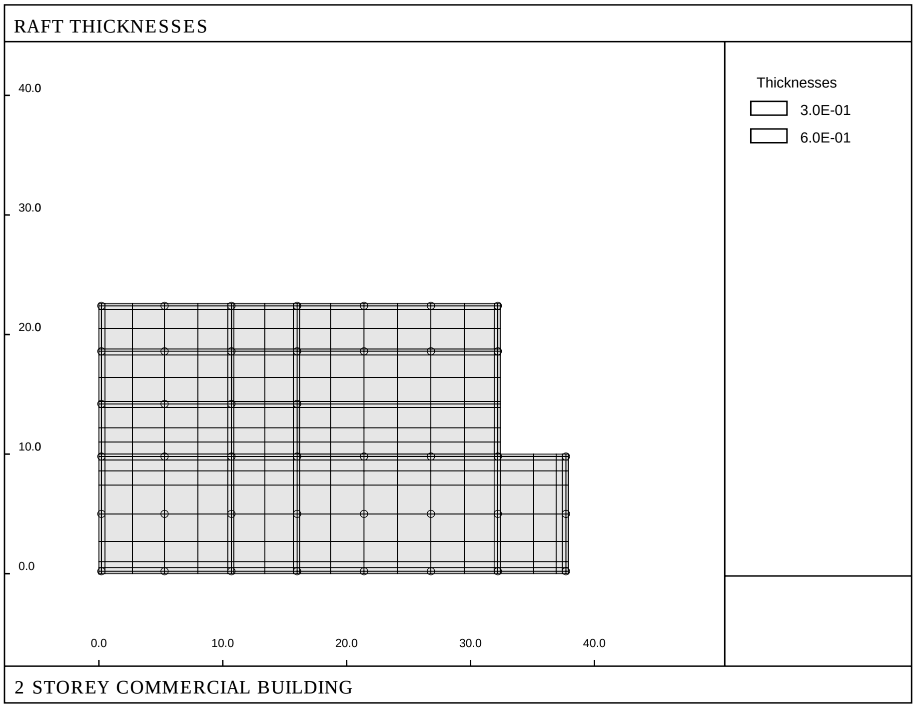


Figure 15: Finite Element Mesh with Stiff Elements at Location of Basement Wall.

Figure 16 shows the settlement contours of the raft from the APRILS analysis. Maximum settlement is observed along the longest side (Side A) of the raft and the minimum settlement is observed along Side B of the raft. A comparison of settlement along Side A of the raft (where the piles are located) from APRILS and GARP is shown in Figure 17. APRILS predicted a maximum settlement of 31.3 mm compared with 27.5 mm from GARP. Along Side A, the differential settlements were 14.4 mm and 13.4 mm for APRILS and GARP analyses respectively.

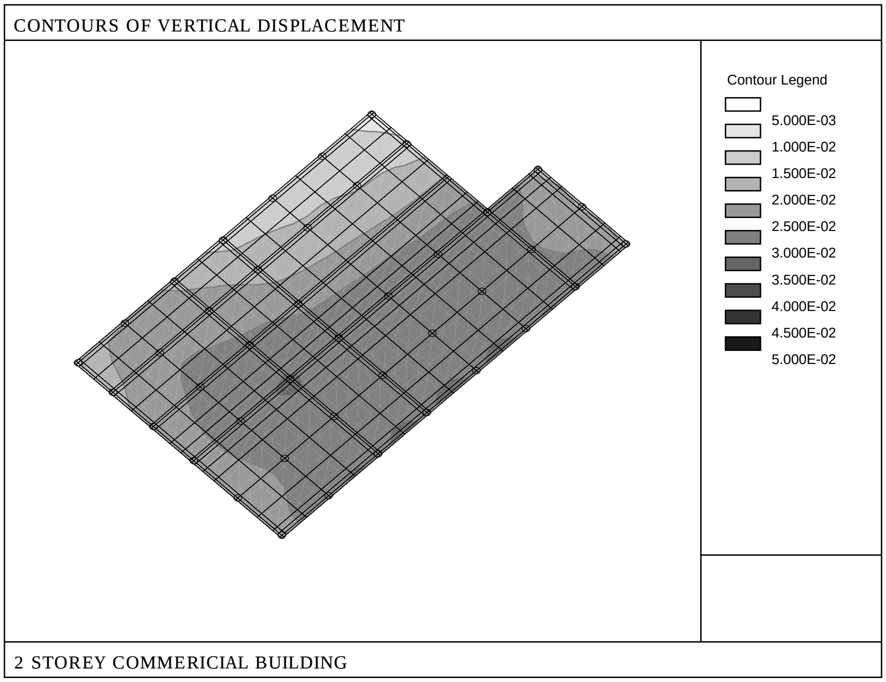


Figure 16: Settlement Contours of the Foundation.

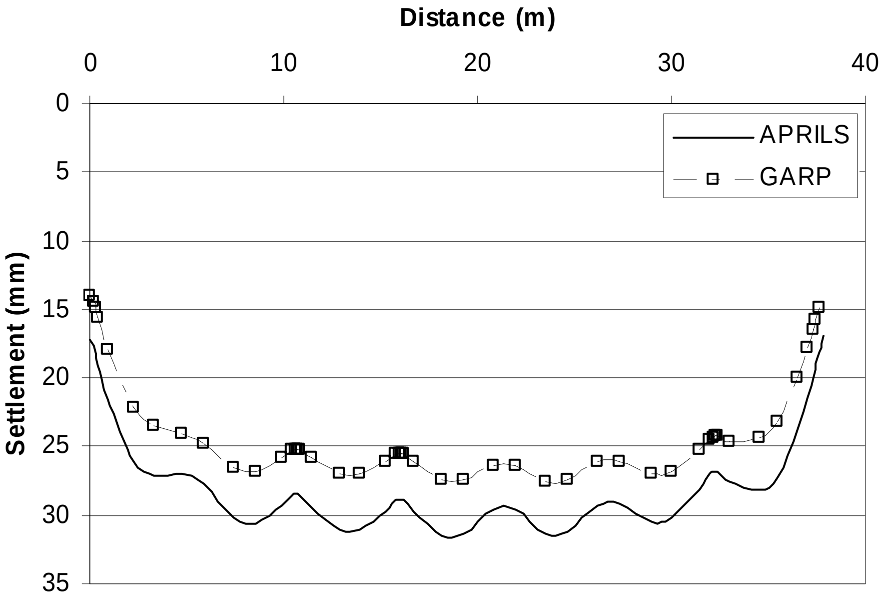


Figure 17: Comparison of Settlement along the Longest Side of the Raft between results from APRILS and GARP.

The pile loads calculated by APRILS are higher than those from the GARP analysis. The piles are carrying about 50% and 65% of the total load based on the GARP and APRILS analyses respectively. This is because in the GARP analyses, the piles are allowed to undergo non-linear load-deflection behaviour and they therefore shed some load to the raft as load increases. Table 3 summarises the maximum and minimum pile load for each pile type based on the two analyses.

Table 3: Maximum and Minimum Calculated Pile Loads for Different Pile Types

Pile Type	Length (m)	Diameter (m)	Max. Pile Load (kN)		Min. Pile Load (kN)	
			GARP	APRILS	GARP	APRILS
1	9	0.6	873	1270	370	484
2	12	0.6	390	544	212	222

4 CONCLUSIONS

Settlement control is one of the major issues in the design of piled raft foundations. When the bearing capacity is sufficient to carry the total structural load, the addition of piles can be used to reduce settlement. Results achieved from the APRILS analyses for the case histories presented in this paper are compared with the actual field measurements and results from Program GARP which employs the boundary element method to compute the interaction. Program APRILS could provide reasonably accurate predictions of the behaviour of piled rafts. For Cases 1 and 2, settlements predicted by APRILS agreed with the field measurements, however, the pile load distribution predicted by APRILS was slightly different from the actual measurements. This could be due to the application of an equivalent uniform load over the foundation which does not model the actual loading conditions. For Case 2, climatic conditions (freezing and thawing periods) appears to have changed the behaviour of the foundation soil which led to the redistribution of the load carried by the piles and raft. For Case 3, the piles and raft are assumed to have an elastic behaviour in APRILS analysis which led to more loads being carried by the piles than for the GARP analysis for which the piles were assumed to have a non-linear load-deflection behaviour.

5 ACKNOWLEDGEMENTS

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