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Raft and piles foundation of a silo

Fondation d'un silo sur pieux encastres dans un radier annulaire

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ABSTRACT

A study of an instrumented silo foundation, constructed in 1996, was undertaken. The foundation was composed of a doughnut shaped raft supported by 20 piles, which were embedded over the entire length in plastic clay having a high water table. The clay extended to a depth of more than 200 meters. The constructed pile length was 21 to 22 m, with a diameter of 1.1 m. Ten of the piles were instrumented with strain gages, spaced at depths of 2 m, 10 m, and 20 m. The raft was based on a well compacted granular soil (kurkar). The head of the piles penetrated approximately 200 mm into the raft, unconnected, in order to enable independent vertical uplift movements. Four pressure cells were placed between the raft and the compacted granular fill. Measurement points for the vertical relative movement between the instrumented pile heads and the raft, as well as elevation points for monitoring the vertical movements of the silo wall, were placed at 8 locations, symmetrically arranged. Systematic measurements for the last 8 years, since the first filling of the silo, were performed. The applications of live loads were recorded on a daily basis and were processed numerically computerized and as diagrams. Early computations for the prediction of load distribution between the raft and the piles were performed by several methods. Observations based on measured data showed large discrepancies during the first 2 years. In the last 6 years, load distribution between the raft and the piles and load transfer along the piles showed steady trends and approached the early predictions.

RÉSUMÉ

Cette communication présente le cas d'un silo construit en 1996, fondé sur des pieux insrtumentés encastrés dans une semelle annulaire. La fondation est constituée d'un radier annulaire reposant sur 20 pieux encastrés sur toute leur longueur dans une argile plastique, la nappe phréatique étant assez haute. L'argile s'étend sur une épaisseur de près de 200 mètres. Les pieux ont une longueur de 21 à 22 m, et un diamètre de 1.10m. Dix des pieux ont été équipés de jauges de contrainte situées aux profondeurs: 2m, 10m, et 20m. Le radier repose, lui, sur une grave compacte (kurkar). La tête des pieux etait encastrée de près de 200mm dans le radier. Quatre cellules de contrainte ont été placées entre le radier et la grave compactée. Les mesures des mouvements relatifs verticaux entre les têtes des pieux instrumentés et le radier ont été réalisées. Les mouvements verticaux du silo ont aussi été aussi suivis à l'aide de mesure en huit points symétriquement disposés. Des mesures systématiques ont été effectués depuis le premier remplissage du silo et pendant une période de 8 ans. Les applications des charges ont été enregistrées quotidiennement, et ont été traitées numériquement, informatisées et traduites aussi sous forme de diagrammes. La prévision de la répartition des charges entre le radier et les pieux a été évaluée par plusieurs méthodes. Pour les premières deux années, les observations basées sur les données expérimentales montraient de grandes divergences. Les six dernières années, la répartition des charges entre le radier et les pieux ainsi que la repatition des charges le long des pieux aux divers niveaux a montré une tendance régulière et s'approchant des premières prévisions.

1 INTRODUCTION

In recent years, considerable work has been done and technical papers have been published, referring to the advantages of "piled raft" foundations, and describing economical design models, (Horikoshi & Randolph, 1998, Hansbo 1993, and others), comparisons of in-situ measurements with numerical analyses, (Reul & Randolph, 2003), and soil-structure interaction, (Katzenbach et al., 2000). Generally, the literature has concentrated on rectangular foundations with piles or circular rafts supported on group of piles. This paper describes the study of an instrumented piled doughnut-raft foundation, with bored piles arranged in a concentric circle. The paper presents the effect of time on the distribution of loads between the reinforced concrete raft and the piles, as well as the differences between the actual load distributions and early assumptions. Other parameters, such as load transfer along the piles and the gap between the raft and piles were also monitored and analyzed. Data presented here consist of continuous measurements from 1996 until 2003.

This work was sponsored by the Nesher factory in order to evaluate further development. The purpose was to understand the behavior or the mechanism of pile-raft-soil load transfer under real working conditions and to aid economic design of similar foundations, in the future.

2 SOIL CONDITIONS

The subsoil in the Nesher cement factory (Nesher), near Haifa, consists of highly plastic, black clay with liquid limit of approximately 100 and plasticity index of 70. The natural water contents vary between 32% and 44%. This stratum was found to extend to a depth of 22 to 25 meters below ground surface. Beneath it, fine dense sand, in a thin layer of about 1 to 5 meters, was found, underlain by more of the same clay to a further depth of more than 20 meters. The upper clay is very soft, up to a depth of 8 to 10 meters, and then it becomes medium hard. The groundwater table at the site, during the soil investigation, was 3 meters below ground level. Later explorations showed that the groundwater table fluctuates to a depth of 6 m, influenced mainly by seasonal changes.

Table 1 indicates the range of the main soil parameters. The parameters are based on in-situ and laboratory tests on undisturbed samples from the site and the surroundings.

Table 1: Soil properties

Parameter	Range
Total unit weight, kN/m^3	17.5-19
Natural water content, %	32-44
Angle of internal friction, deg.	18-22
Cohesion, kPa	20-60
Undrained shear strength, kPa	43-78
Poison ratio	0.25
Over consolidation ratio	1.0-4.5
Compression index, C_c	0.34-0.57

3 STRUCTURE AND FOUNDATION

Silo No. 12 was 20 m in diameter and 40 m in height. The dead load of the structure was 40,000 kN, with fluctuations of the live load up to 100,000 kN. The silo was built on a doughnut shaped, very rigid raft between 0.5m and 1.5m thick,, supported on 20 piles. The outer diameter of the raft was 24.1 m and the inner diameter was 15 m. The silo walls had an outer diameter of 20 m. and were concentrically placed on the raft by rigid walls having openings for the accommodation of cement-loading lorries. The supporting piles were 20 to 21 m. long with diameter of 1.1 m., and separated 2.75 m o.c. The raft was constructed on 1.4 m compacted granular subgrade. The piles were embedded into the raft but not connected to it, so that pullout loads would not be transfered to the piles when the silo was emptied, or during rise of the water table. The piles were not embedded in the lower granular stratum, due to the possible danger of punching it where this stratum was thin.

4 EARLY COMPUTATIONS AND EVALUATIONS

Analyses of piled rafts which were published, at the time of the design of Silo 12, by several authors (e.g. Hansbo, 1993, Poulos, 1993), referred, mainly, to pile groups, interacting internally and externally with the raft. Some work was also performed for single piles taking into consideration the effect of the slenderness ratio, l/d (equal to 19 in the present case).

The piled raft of Silo 12 could not be considered as a raft supported by a group of piles, nor by single piles, due to the undefined behavior of a circular line of piles separated 2.5d. o.c. However, due to the high rigidity of the raft and the upper structure, the piles could act only as a group. Early computations were considered not sufficiently reliable. In such a situation, interaction was, practically, hard to predict. A preliminary approach was taken to ensure that the settlement would be large enough to fully mobilize the piles to reach a state of constant load carrying capacity, close to a factor of safety of 1. The pile tips were assumed not to carry any load, because the medium plastic clay extended for another 2 - 5 m below the tips.

After evaluating the load carrying capacity of all 20 piles, the remaining load was to be transferred to the soil by the raft. The problem was how accurately the load carrying capacity of the friction along the shaft could be computed. Over-design of this factor could have been very dangerous to the raft. Therefore, the first assumption was based on the computed pile-soil friction for a factor of safety of 1, and the second assumed the piles would carry only half of the computed shaft-soil friction.

For the first assumption of a factor of safety of 1, all 20 piles could provide a total load of 112,000 kN; therefore, 20% load was to be carried by the raft and 80% by the piles. For the second assumption of load division between piles and raft, the proportion was 40% for the piles and 60% for the raft, i.e. 56,000 kN and 84,000 kN, respectively. The raft was actually designed to carry a maximum of 60% of the load, on the assumption that the silo may permanently be filled to its maximum capacity, i.e.. 40,000 kN dead load and 100,000 kN live load. Load fluctuations were completely unpredictable; therefore settlement computations were done for the maximum load to be transferred by the piles - 112,000 kN or 5,600 kN per pile. It was also assumed that each pile would carry the same load, and the contact stresses of the raft would be equally spread over the entire area of the raft. Consequently tilting was not taken into consideration, while it was clear that some minor tilt would occur. Another unknown factor was the time effect on the distribution of the loads and its consequences, especially during the first and fast filling of the silo.

5 MONITORING INSTRUMENTATION

Having experienced difficulties with excessive settlement and tilting of the nearby silo no. 11, which reached a maximum tilt of 275 mm and an average settlement of 420 mm within 3.5 years, it was deemed necessary to reduce settlements by adding piles to silo no. 12, and to monitor the behavior of the new silo. The monitoring consisted of the following: 10 of the 20 piles supporting the raft were instrumented with strain gauges at three levels: -2m; -10m; -20m. 4 pressure cells were fixed between the raft and the granular subgrade in order to record contact stresses. 4 extensometers were placed between the raft and the pile heads in order to measure relative vertical displacements during silo heave. 8 benchmarks, equally spaced, were placed around the silo walls, to enable recording of vertical movements. The layout of all monitoring devices is shown in Fig. 1. The live load fluctuations were also recorded.

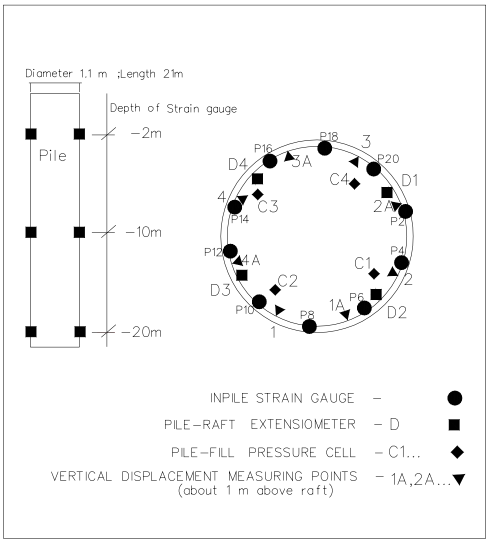

Figure 1. Monitoring Devices Setup.

6 MEASUREMENT RESULTS

Measurements were recorded continuously and are shown in Fig 2. The average settlements with the differential vertical movements (tilt)on two perpendicular diameters were computed and are shown in Fig 2a. Load vs. time, as recorded by the factory, together with a general average load, are shown in Fig. 2b. The following observations were made:

During the first 90 days of loading, up to 130,000 kN (93% of full capacity), the settlements developed rapidly to 42 mm, at an almost constant rate of 0.47 mm/day. During this time the maximum recorded tilt reached 20 mm, i.e. an average of 0.22 mm/day, almost half of the total average settlement.

During emptying of the silo to 40,000 kN within 20 days, the average settlement decreased to 32 mm The unloading did not change the differential settlements on either diameter.

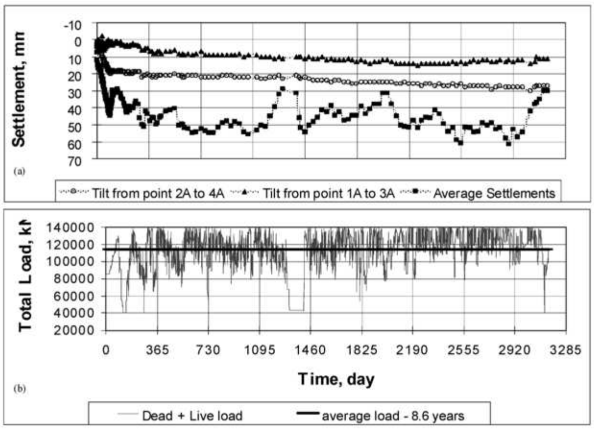

Figure 2. Load-settlement-time diaghram.

During more than 8 years of observations, the silo did not recover from the initial tilt which increased slowly at a rate of about 1.1 mm/year.

The settlement reached a maximum of 51 mm within one year and then reacted to loading and unloading by settling 29 mm to 61 mm with temporary recoveries of up to 25 mm.

The 4 pressure cells, which were equally spaced between the raft and the granular compacted fill, showed that during the first 90 days the load varied enormously, by up to 30,000 kN/cell. The average load was 17,000 kN/cell, with a total load of 68,000 kN (or 48.6% of the maximum possible load) transferred to the whole raft. The large variation indicated by the pressure cells decreased in time and after one year the load decreased to only 20% of the total load, but the cells went out of order and further readings became impossible.

The four extensometers installed to measure the relative movement between the pile heads and the raft, detected less movement than the accuracy and resolution of the equipment. In the early stages, separation between pile heads and raft during unloading reached 1.5 mm, while in later stages no relative heave occurred. It is believed that the heave affected the raft and the upper part of the piles similarly. After reloading, raft and pile heads came into contact.

Ten alternate piles of the 20 supporting the raft were instrumented with strain gages before the construction of the raft. However, the readings commenced only at a later date; therefore, negative friction, (if it existed) could not have been detected. The raft was constructed and finished only about one month after the piles were in-place and the filling of the silo started only 4 months after the beginning of the construction. Measurements commenced while the construction was about half finished, which was 2 month before the first filling of the silo. While examining the load transfer to the piles, it was noticed that there were major differences between piles. This was due mainly to the heterogeneity of the soil at the site, but also due to the possible uneven distribution of cement-loads within the structure. These differences were also time dependent. The loads in each pile at the different measurement depths, 500 days after the first readings, when the total load was 95,000 kN, are shown in Table 2.

Figure 3 shows the average load transfer in the piles as a function of depth and time. The average friction in the upper eight meters of the piles changed significantly during the first two years, as seen especially in the 05/04/97 and later measurements. Afterwards, the load transfer became almost constant. The friction in the upper 8 meters was about 176 kN/m and that in the lower 10m was about 106 kN/m. The rest of the loads carried by the pile were transferred to the soil by the upper 2 m, and the lower 1 m (approx.) by the pile tips. It is possible that the upper 2 m of the pile improved the local carrying capacity due to the top 1.4 m of compacted granular fill.

The pile friction measured on the upper parts of the shafts during the early stages of the loading, was close to 5 times that on the lower parts of the shafts, but the distribution changed after the first two years. The loads carried by the pile tips changed less erratically than the friction. After the first 2 years, the tips contributed about 2,000 kN per pile or a total load of 40,000 kN, which was almost 30% of the total possible service load. The increasing settlement caused increasing participation of the pile tips for almost the first two years, but it then remained practically constant, unaffected by live load variations.

The load was not shared equally between the piles. In the first years, some piles carried almost twice the load of others, as in Table 2. Presently, 8.7 years after the first loading, there are still some differences; some of the piles are loaded almost 20% above the average and others are under-loaded.

Relative heave, as measured between pile heads and raft, was negligible. If the pile heads heaved similarly to the raft, then the upper part of the piles stretched upwards, thus the heave caused strains on the piles. This may prove to be the main danger to the piles by increasing the rate of corrosion of the reinforcement.

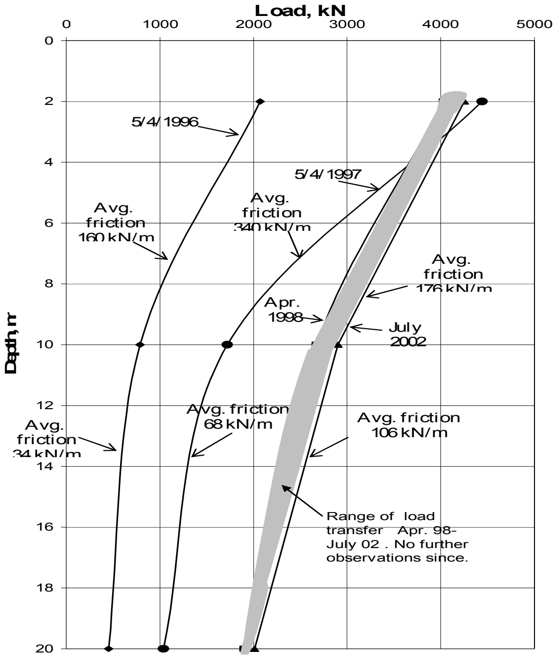

Figure 3. Load transfer pile/soil by friction

Table 2: loads on piles at various levels.

Pile number	Load, kN		
Depth, m	-2	-10	-20
P2	4780	3240	2430
P12	5530	3210	1980
P4	4320	2270	1570
P14	2290	1560	990
P6	2490	1650	1720
P16	3890	2060	790
P8	2460	2070	1120
P18	3010	1560	970
P10	4230	3080	2020
P20	4870	2780	1650
Total	37870	23480	15240

7 ANALYSIS

The erratic changes of the applied loads generate variations in the total settlements up to certain values, but did not affect the slow increase of the differential settlements (tilt), as shown in Fig. 2a. Fig. 4 shows the relative distribution of load between the raft and the piles. Foundation behavior changed dramatically with the elapse of time. In the early stages, the raft carried much beyond the early predictions. After about 2 years, the raft contribution diminished to less than 25% of these assumptions and kept diminishing slowly.

Design, which was based on computed values, underestimated the loads to be carried by the raft in the early stages. Such a design could have been disastrous causing a construction failure of the raft. The piles were not very sensitive to overloading.

After slightly more than 2 years the load sharing between raft and piles became practically stable: 12 - 15% carried by the raft and the rest by the bored piles, in friction and tip bearing.

The lower 10 m of the piles behaved in a more gradual manner almost from the start of the loading. While in the upper 8 m, the average friction changed from 160 kN/m to 340 kN/m and then to 176 kN/m; the lower 10 m changed gradually in time from 34 kN/m to 68 kN/m and then to 106 kN/m. This data represents the following years of loading: 1 year, 2 years and up to 5.5 years of loading.

An important parameter is the elastic/plastic behavior of the soil. During the first 50 days the downward movement was rather fast, up to 18 mm, and never recovered completely. The filling was done at a fast pace for the 68 following days and settlement continued evenly to an average of 44 mm, while the maximum tilt also increased steadily to 19 mm.

After emptying the silo, 170 days after the first filling, the upward average movement was impressive, reaching about 28 mm.

This loading and unloading showed some vertical movements:

When emptying of the silo began,, the settlement did not stop for about 10 days, but during reloading, the settlement started immediately.

The slope of the load-settlement curve during the first filling of the silo reached 2900 kN/mm and the recovery line was lightly steeper for some 20 days.

Loading and unloading increased and decreased the settlement without exhibiting full recovery. Later loading and unloading caused settlements and heaves of the same order of magnitude.

Settlements and recoveries showed a definite repetitive elastic behavior with a slight creep of about 5 mm/year. It seems that the first fast loading caused a partial shear with residual settlement. Was the distribution of later loadings between raft and piles affected by the fast loading? If yes, it may have an important bearing on the whole mechanism, but the present study does not propose an answer to this question.

After the original tilt of 20 mm, it continued at an approximate steady rate of about 1.5 mm/year, for the next 7.7 years of measurements. This is practically constant and it is apparently not affected by the loaded or unloaded state. It is probably connected to the variations in the clay properties and the unevenness of the thickness of the clay strata beneath the pile tips. In such a situation, the tilt is probably due to creep phenomena and not related to consolidation of the clay strata.

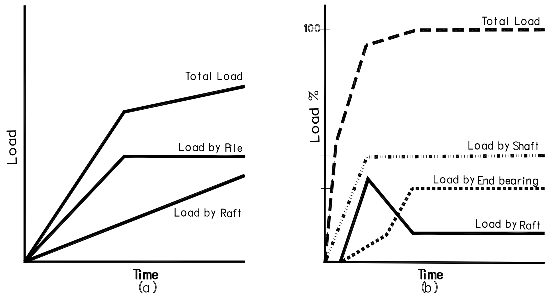

Figure 4. Load Transfers- Schematic Model. a) Classic b) Real

8 CONCLUSIONS

Considering the soil condition at this site, the combination of a pile and raft foundation achieved its purpose of reducing settlements to a fraction of those incurred by the adjacent silo no. 11. The records from the instrumented piles and the other measurements helped to understand the mechanism of the interaction between pile-raft-soil elements. The available data is a base, which could serve further investigations, including numerical computation and other existing design methods. The measurements showed large changes in the load distribution between the piles and the raft in the early days, but remained stable for about two years. At the beginning of the silo lifetime, the load distribution between the raft and the piles was not according to calculations or according to prediction, and changed frequently. After about 600 days of loading, the relative proportions of load carried by the raft and piles became stable, with the relative load on the raft at 12% to 15% and the remaining load carried by piles. Lower overall imposed load resulted in lower loads carried by the raft and the piles, but in the same proportion. The load carried by the piles differed significantly from pile to pile.

After sufficient vertical movement developed, in this case about 55 mm, or about 5% of the pile diameter, the pile tips shared a substantial part of the total pile load with the remainder carried by friction between the shaft and the surrounding soil. This data could not be fully determined from the measurement made for this study.

The “gap” between the raft and top of piles showed insignificant changes, indicating that differential upward movements between them are negligible. The decision not to connect the piles and raft structurally appears to have been superfluous.

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