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Large storage capacity cement silos and clinker deposit on a near-shore sandy fill using piles for soil improvement and settlement reduction

Silos de stockage de ciment de grande capacité et dépôt de clinker sur un remblai de sable près de la côte en utilisant des pieux pour l'amélioration du sol et pour la réduction des tassements

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ABSTRACT

An important terminal and cement grinding plant is today under construction on a 10 m thick near-shore sandy fill inside the Castellón harbour area (Spain). The main structures of the cement production plant consist of a 540 MN silos system (70 m high) and a deposit, covered by a 62 m diameter dome, which is able to store up to 800 MN of granular clinker. The natural subsoil conditions of the area are very complex, from the geotechnical point of view, due to the alternation of locally lightly cemented silty and gravelly sands and quasi normally-consolidated and structured fine grained materials. The foundation design of such installations considered the use of driven cast in-situ concrete piles (0.4 m in diameter and about 12 m in length), to densify the near-shore structural sandy fill, and bored piles (1.5 m in diameter and 48 m in length) to reduce the total and differential settlements. The subsoil geotechnical profile, the foundation design approach and the final layout of the driven and bored piles are illustrated with particular reference to the silos system. Data from the operating monitoring system are also reported in terms of total and differential settlements of the piled raft and of the load sharing among the bored piles, driven piles and in between soil up to the end of the construction stage of the silos structure, which represent about 35% of the total load expected at the foundation level during the service stage.

RÉSUMÉ

Une importante usine de broyage de ciment est aujourd'hui en cours de construction sur un remblai de sable près de la côte épais de 10 m, situé à l'intérieur de la zone portuaire de Castellón (Espagne). Le système de silos de 540 MN (70 m de haut) et le dépôt de 62 m de diamètre, capable de stocker jusqu'à 800 MN de clinker, sont les principales structures de l'usine. Du point de vue géotechnique, les conditions naturelles du sous-sol sont très complexes en raison de l'alternance de niveaux locaux légèrement cimentés de sables limoneux et graveleux et de matériaux à grains fins, structurés, presque normalement consolidés. Dans le projet des fondations des structures on a examiné l'utilisation de pieux à tube battu coulés en place (0,4 m de diamètre et environ 12 m de longueur) pour la densification du remblai de sable près de la côte et de pieux forés (1,5 m de diamètre et de 48 m de longueur) pour la réduction des tassements totaux et différentiels. L'article présente le profil géotechnique du sous-sol, le projet des fondations et le choix final des pieux forés et battus, se référant en particulier au système des silos. En outre, les données du système de monitoring installé sont présentées en termes de tassements totaux et différentiels pour les radiers de fondation à pieux et de distribution de la charge entre les pieux forés, les pieux battus et le sol jusqu'à la fin de la phase de construction de la structure des silos, qui représente environ le 35% de la charge totale attendue au niveau des fondations à l'état de service.

Keywords : Silos structure, piled raft, settlements, monitoring system

1 INTRODUCTION

One of the most important cement industry in the world is involved in the extension of the Castellón harbour area (Spain) in order to build a terminal and cement grinding plant, that will be able to produce up to 600000 tons per year of cement. The main structures of the plant (Figure 1) consist of a 540 MN silos system (including the self-weight of the structure and of the raft foundation) and a deposit, covered by a 62 m diameter dome, which will be able to store up to 800 MN of granular clinker. Considering the size and weight of these structures and the very complex subsoil conditions, which involve both a recent fill, made up of dredged soil, and fine grained quasi normally consolidated (NC) natural deposits, the foundation cost constitutes one of the main items of the total budget for the plant construction.

In order to optimize performances and costs, the use of piles as settlement reducers (Burland et al, 1977; Burland & Kalra, 1986; Viggiani, 1995; Katzenbach et al, 1997; Mandolini et al., 2005; De Sanctis & Russo, 2008) was considered from the very beginning of the foundation design stage for the main structures of the plant. Moreover, since short driven piles have resulted to be more effective and cheaper than other locally available soil improvement techniques, they have been adopted to increase the

vertical stiffness and density of the recent 10 m thick fill made up of dredged silty sand.

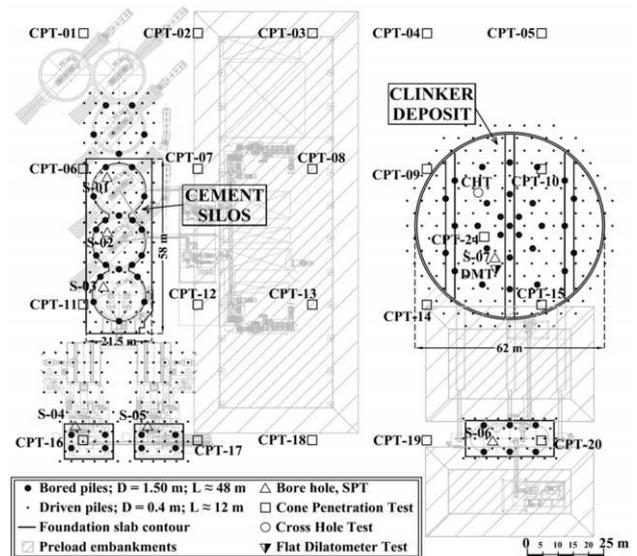


Figure 1. Design layout of the terminal and cement grinding plant.

The monitoring devices installed on the foundation system were defined to supply information on the total and differential settlements of the raft foundation and on the load sharing among the bored piles, driven piles and in between soil. The structure of the silos system, whose self-weight corresponds to 35% of the total load expected at the foundation level, has been completed but has still not been filled with the cement. Nevertheless, the first series of significant data from the installed monitoring instrumentation is now available and can be used to assess the actual foundation behavior and predict the settlement evolutions under the full design load in the most reliable way. The first series of measurements from the monitoring system are presented in this paper and compared with the result from a numerical model implemented on NAPRA (Russo, 1998; Mandolini et al., 2005; de Sanctis & Russo, 2008) the computer code which has been used for the final design of the piled raft.

2 SUBSOIL PROFILE

The seabed inside the considered area was originally located at about 7 m below the medium sea level (m.s.l.). The final ground level (g.l.) was raised up to about 2 m above the m.s.l. by a dredged silty sand fill.

Underneath the artificial fill, the natural subsoil conditions of the area are very complex from the geotechnical point of view due to the alternation of locally lightly cemented silty and gravelly sands, in the upper part of the subsoil profile, and quasi normally-consolidated and structured fine grained materials, with thin sand lenses inside, located at a depth between 25 and 43 m. Below these formations, a coarse and dense soil deposit prevails to the maximum depth investigated by the boreholes (i.e. 60 m). Silt and clay inclusions were also detected inside this coarse deposit.

Figure 2 shows a sketch of the previously summarized subsoil profile and some typical results of in situ tests from the main geotechnical investigation campaigns which consisted of Bore Holes (BH) with undisturbed soil sample recovering, Static Cone Penetration Tests (CPT), Standard Dynamic Penetration Tests (SPT), Flat Dilatometer Tests (DMT) and Cross Hole Tests (DH) (see Figure 1 for the location).

It is interesting to note, from Figure 2, the significant increase in CPT point resistance (q_c) within the sandy filling after the driven pile installation has been completed and the very low number of blows (N_{spt}) from SPT and q_c values inside some layers of the silty clay formation located at a depth between 25 and 43 m. Moreover, the latter formation also shows some evidence of possible slightly structured fabric, as pointed out by some oedometer test results, compared with the intrinsic compression line (ICL) and sedimentation compression line (SCL) according to Burland (1990).

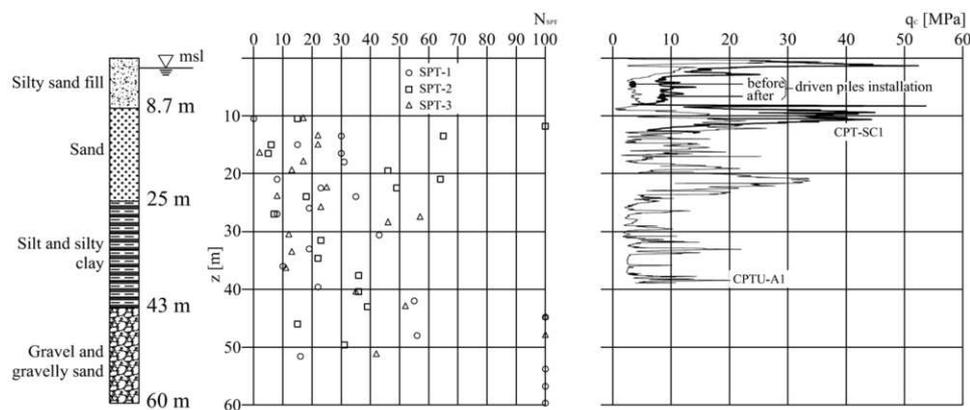


Figure 2. Subsoil profile and typical field test results.

3 FOUNDATION LAYOUT OF THE SILOS STRUCTURE

Figure 3 shows the foundation layout of the silos structure in detail. The first block of 3 cylindrical silos is the one that is presently built. The construction of the fourth silo is planned for the near future. The piled raft has a thickness of 1.8 m and the footprint dimensions are reported in Figure 3. The short driven cast in place concrete piles are 0.4 m in diameter and about 12 m in length. They are situated in an equilateral triangle pattern with a spacing of 3.8 m. One hundred ten driven piles have been installed to reinforce and improve the near shore sandy fill underlying the raft foundation of the silos. Moreover, nineteen large diameter bored piles have been installed under the three silos. The bored piles are 1.5 m in diameter and 48 m in length.

The adopted design approach involves the use of piles as settlement reducers. The bearing capacity of the unpiled raft was judged more than sufficient to reach the minimum safety levels indicated by Eurocode EC7. Therefore the piles have been designed in order to keep the maximum silos settlement below 15 cm and the maximum foundation rigid tilt under 1/500, as required by the client.

The pile bearing capacity has mainly been assessed referring to the SPT and CPT tests carried out after pile driving and to the related empirical relationships with the pile side and tip bearing capacity as summarized by Manassero et al. (2005). The theoretically estimated total bearing capacity (i.e. 24 MN for the bored piles and 1.2 MN for the driven piles) has been verified through in situ load tests and the load settlement curves have been used to calibrate the input parameters of the theoretical model implemented in the NAPRA code.

After the optimization of the number of piles, the theoretical model has predicted a maximum settlement of about 12–14 cm. This result and the related load distribution among the piles and soil are compared in detail with the monitoring data in the following points.

4 PREDICTION VERSUS PERFORMANCE

The settlements of a number of targets installed on the piled raft were monitored by an optical survey. The loads directly transmitted by the raft to some driven and bored piles were also measured through vibrating wire strain gauges applied to the reinforcing steel cage and hydraulic pressure cells located close to the pile top. Moreover, the vertical load distribution along the shaft of the bored pile n. 44 was measured through a series of instrumented sections located at different depths along the steel cage. To complete the field instrumentation, a series of hydraulic vibrating wire pressure cells were installed at the interface between the soil and the raft in order to be able to appreciate the vertical pressure component transmitted directly by the raft to the soil between the driven and bored piles. The position of the aforementioned monitoring devices is shown in Figure 3.

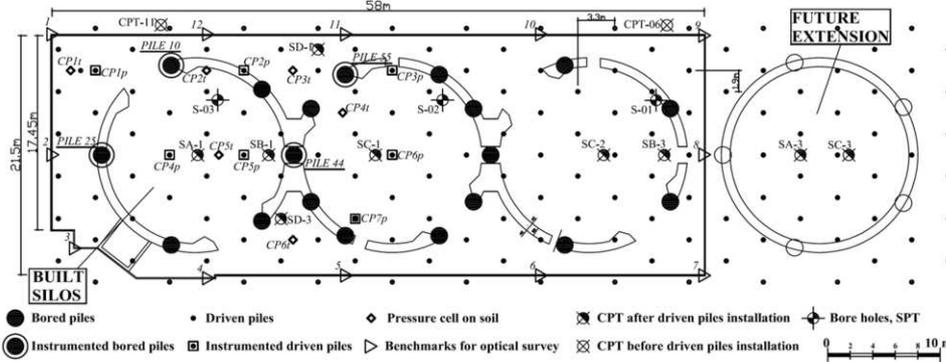


Figure 3. Silos foundation layout with related instrumentation and targets for optical survey.

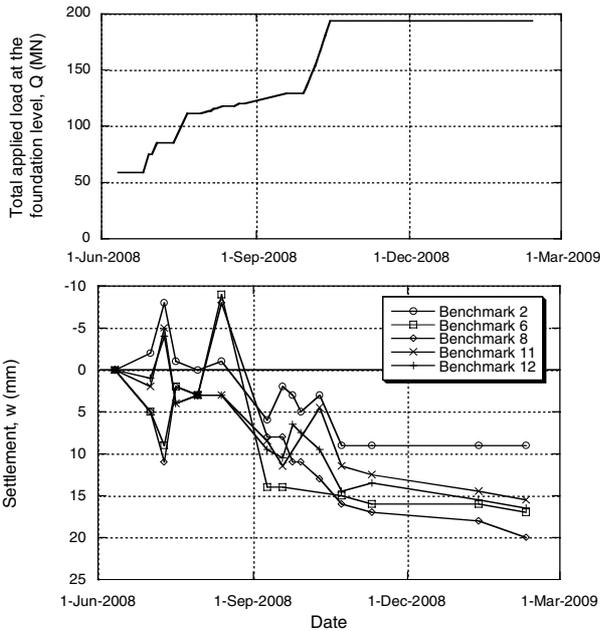


Figure 4. Load history and settlements of the silos piled raft.

The total applied load at the foundation level versus time is plotted in the upper part of Figure 4, while the measured settlements are plotted in the lower part. The settlement observations were started after completion of the raft, therefore the measurements cannot provide any information on the immediate undrained ground movements due to the self-weight of the raft. Nevertheless, considering the construction time history and the consolidation features of the fine-grained soil layers, at least a significant part (i.e. more than 50%) of the consolidation component of the total settlement has probably been picked up by the optical survey. Moreover, the long term measured settlement values under the total self-weight loads of the structure can be considered very close to the final consolidation settlements according to both theoretical evaluations that were carried out during the design phase and the average loading rate that occurred during the silos construction stage. The measured settlements, at some of the most representative locations, versus the applied load are shown in Figure 5. The settlements predicted during the design phase at the measurement points are also reported in the same figure up to the final maximum service load of the silos. Apart from the scattering of the monitoring data, the agreement with the theoretical simulation can, on average, be considered rather good for engineering purposes. The theoretical curves representing the settlements versus the total load applied up to the maximum service load foreseen on the silos can be considered a useful tool for the prediction of the maximum settlements and to check the structure behaviour in particular during the first complete cycle of filling operations.

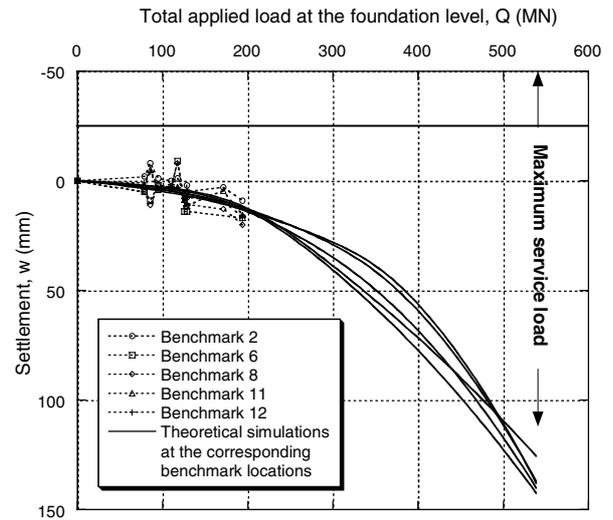


Figure 5. Measured and theoretically predicted values of settlements versus total applied load on piled raft.

Figure 6 shows the final settlement profile along the longitudinal axis of the piled raft, as detected from the optical survey at the end of the silos construction stage. Again in this case, the agreement between the design model prediction and the observed piled raft behavior is on average acceptable, at least up to the present load level, but further observations are necessary before a more reliable judgment on the piled raft deformation and its bending behavior versus the applied loads can be obtained.

The settlements of the instrumented piles versus the head loads acting during the construction phase are shown in Figure 7 together with the corresponding theoretical curves up to the maximum design service load. The theoretical curves have been assessed via the NAPRA code that is able to take into account the interactions among the foundation piles. In this case, the comparison of the measured and theoretical results seems to be particularly good, but also in this case further loads must be applied to confirm the present very good agreement.

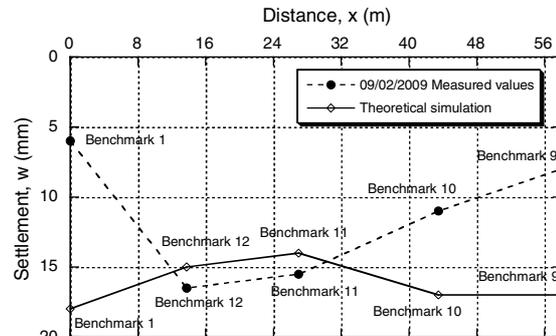


Figure 6. Measured versus theoretically predicted values of settlements profiles along a longitudinal alignment of the piled raft.

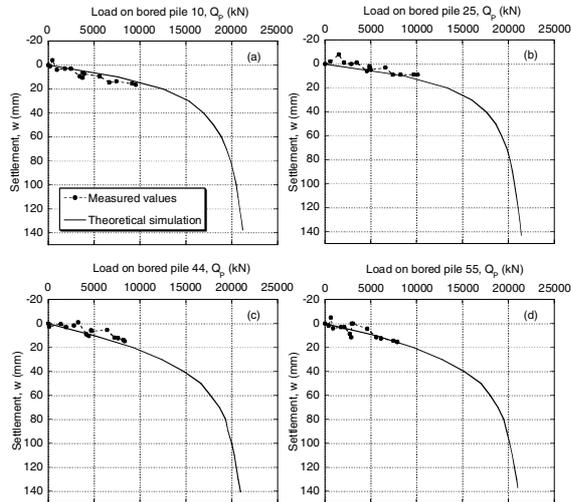


Figure 7. Measured versus theoretically predicted values of settlements versus load on instrumented bored piles head.

The total load during the silos construction stage and the percentage carried by the bored piles are reported versus time in Figure 8. The total load in this plot includes the self-weight of the raft which, due to the consolidation processes that occurs within the fine grained soil layers, progressively moves from the soil, at the end of the casting operations, to the piles, at the end of the consolidation process. The measurements of the vertical pressures on the soil at the raft interface and of the loads acting on the short driven piles, from the loading cells located as shown in Figure 3, enable us to obtain a direct estimation of the percentage of the total load carried by the driven piles and the surrounding soil. Moreover, a comparison with the complementary value from the measurements on the bored piles can be exploited to assess the reliability of the monitoring system results.

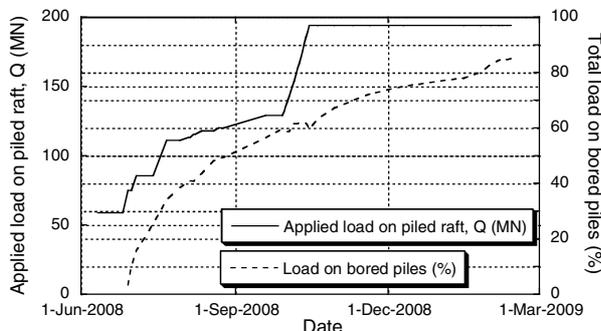


Figure 8. Load sharing between bored piles and reinforced soil underneath the silos raft.

The average measured pressure on the soil resulted to be about 15 kPa and the average load, on each driven pile, about 100 kN. Considering that the area of the raft print is about 1247 m² and the total number of driven piles underneath the silos raft is equal to 110, the load share carried by the soil is about 19 MN and the load share carried by the driven pile is 11 MN. The combination of these contributions results in a partial load equal to 30 MN. If the complementary partial load expected on the 19 bored piles, on the basis of the values measured on the instrumented ones, at the end of the construction phase (about 164 MN) is added to the soil and the driven pile contribution, a total load of 194 MN is obtained. This value is fully consistent with the self-weight of the three silos and the related raft foundation, therefore, the overall reliability of the monitoring system measurements, up to now, seems to have been validated.

5 FINAL CONSIDERATIONS

Presently, about the 85% of the load due to the self-weight of the silos system is carried by the large diameter bored piles designed as settlement reducers. This value is high compared to the literature indications for the same types of piled raft geometry (Viggiani, 1995; Katzenbach et al, 1997; Mandolini et al., 2005; de Sanctis & Russo, 2008). This apparent inconsistency can be explained considering that only the 35% of the total load expected at the foundation level at present acts on the piled raft and, therefore, the bored piles are still working close to their maximum stiffness i.e. within the quasi-elastic range that occurs at small strains. When the further loads are applied to the piled raft during the first filling operations of the silos, they are expected to move from the large diameter bored piles to the surrounding soil reinforced by the short driven piles.

Up to now, the measured settlements versus loads at the different raft locations are on average in very good agreement with the theoretical predictions obtained using the NAPRA code for piled raft design (Russo, 1998; Mandolini et al., 2005; de Sanctis & Russo, 2008) and referring to the soil characterization carried out on the basis of a large number of different types of in situ and laboratory soil tests.

The settlement evolution during the first filling stage of the silos, up to the maximum expected load, will be observed and interpreted in light of the aforementioned theoretical model and the final results of this interesting case history will be published as soon as they are available in order to offer a further practical contribution to the advancement of pile foundation design.

ACKNOWLEDGEMENT

The Authors would like to thank Buzzi Unicem Ltd (Casale, Italy) for the care taken concerning the foundation problems and the financial support for the installation of the monitoring system which was well above the requirements for standard design and construction approaches.

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