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Construction, design for soil structure interaction and monitoring of the pile foundation of a high-rise building

Construction, dimensionnement basé sur l'interaction sol structure et mesure de tassement d'une fondation sur pieux d'un bâtiment de grande hauteur

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ABSTRACT The foundation of the Sofaz tower in Baku was initially foreseen as deep bored piled foundation, executed from the bottom of the already excavated pit. During the pre-testing period, a deep water bearing layer was discovered with a piezometric level significantly above the excavation level. An alternative foundation design was therefore developed, maintaining the level of the piles above the deep water bearing layer. The piles are mainly embedded in relatively soft layers and their end bearing capacity is rather small. Due to these soil conditions and the short length of the piles, their close center-to-center distance, and the high load of the tower itself and the lower of the surrounding podium, a soil structure interaction analysis was performed using a geotechnical FEM program Plaxis to simulate the interaction between raft-pile and soil, and a structural 3D model in which the piles are modelled as uncoupled springs. Both program were used in turn: the geotechnical program to assess the settlement in a soil-structure interaction under a given load pattern on the foundation, and hence determine the spring stiffness to be used in the structural code, while the structural code was used for determination of the loads on the piles accounting for the stiffness of the whole tower and podium. Both programs were used in turn until convergence of pile head settlement in both was obtained. A settlement monitoring system was set up and maintained up to 15 months after the end of concrete works, to check the predictions.

RÉSUMÉ La fondation de la tour Sofaz située à Bakou était initialement une fondation sur long pieux forés exécutés depuis le fond de la fouille existante. Durant la phase de pré dimensionnement, une nappe captive profonde a été découverte avec un niveau piézométrique significativement plus haut que le niveau du fond de l'excavation. Une variante de dimensionnement de la fondation a donc été développée en positionnant le niveau inférieur des pieux au-dessus de la nappe sous pression. Les pieux sont supportés par friction dans des couches de sol relativement meubles et par une pointe de résistance plutôt faible.
Au vu de ces conditions de sol, de la faible longueur des pieux, de la faible entre-distance entre pieux, de l'importante charge localisée sous la tour par rapport aux charges sous le podium environnement, une analyse interaction sol-structure a été réalisée au moyen du programme aux éléments finis Plaxis afin de simuler l'interaction entre le radier fondé sur pieux et le sol, et un modèle 3D représentant la structure dans lequel chaque pieu est modélisé par un ressort spécifique. Chaque programme a été utilisé en alternance: le programme géotechnique définissant le tassement résultant de l'interaction sol structure et définissant par conséquent la raideur des ressorts à employer dans le modèle structure, tandis que le modèle structure a été utilisé pour déterminer les charges sur les pieux en tenant compte de la raideur de la tour et du podium. Les deux programmes ont été utilisé en alternance jusqu'à l'obtention de la convergence des tassement en tête de pieux dans les deux modèles. Une campagne de mesure des tassements a été réalisée pendant la construction et jusqu'à quinze mois après la finalisation des éléments en béton de la structure.

1 INTRODUCTION

In the present paper, we will describe the inventive method used to optimize the soil-structure interaction for high-rise buildings and the new development in finite element program permit to avoid overdesign of structures. The method has been applied to the Sofaz project in Azerbaijan.

2 THE PROJECT

Sofaz is a high-rise tower of 132m built in the new administrative center in Baku. It offers 24 floors and 2 basement levels. The circular podium levels (from ground floor to level 3, diameter 50m) contains all shared functions, such as entrance lobby, library, conference rooms, restaurant, museum etc.

The whole concrete structure has been built on a piled raft (70m by 70m) situated 10 meter below ground level.

The preliminary design of the foundation was considering concrete bored piles (diameter 1.2m) with a length of 31m crossing an impervious clay layer situated 12m under the raft.

From the geotechnical site investigations, is was deducted that two water tables are present: one above the clay layer and a confined aquifer below the impervious layer. The water level in the confined aquifer is about 7 meter above the top of raft level.

As the general excavation (about 10m) of the area had been already performed, the execution of 31m bored piles would lead to a waterflow over the top of the pile casing. Several options were investigated to avoid uncontrolled flow of water and guarantee the quality of the piles:

- Installation from a working platform situated at least 1.5m above the highest water level
- Lowering of the ground water level
- Excavation with a casing and supported by fluids when drilling is continued under the casing.

Due to the complexity of the execution of the 31m bored piles, a solution with shorter piles has been considered to avoid drilling through the impervious layer.

3 GEOTECHNICAL AND HYDROLOGICAL CONDITIONS

Four soil investigation campaign were available in the vicinity of the site.

3.1 Geotechnical conditions

The soil stratigraphy in Baku is characterized by an upper limestone layer of almost 8 m thickness. Most of the buildings in the area are founded on this limestone and do not required any deep foundation system.

Under the Sofaz tower, a 10 m depth basement was foreseen which implies the removal of the limestone layer and to found the building on the underlaying soft layers.

Under the removed limestone layer, the soil investigations have shown a loam and clay layer of 8 m overlaying a clay layer of around 6 m. At 28 m depth a fissured limestone layer of 7 m has been encountered and finally a sand layer from 35 m depth up to 50 m.

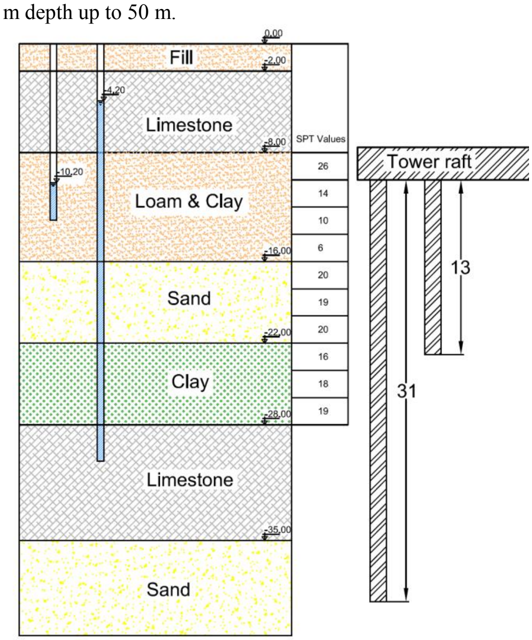

Figure 1. Typical soil profile

3.2 Hydrological conditions

The site hydrology is characterized by several water tables at different levels. A surface water table fed by rain water, a free water table in the loam layer (9m depth) and a confined aquifer underneath the clay layer (-31m) with a pressure measured in piezometric standpipe of -4.2 m under the reference level.

4 PILE TEST

At the tower location, 3 static compression pile load tests (PLT-1; PLT-2; PLT-3) were performed. The test piles were 1.2 m dia. and 31 m long bored piles of 6 666 kN design capacities. Reactions were provided by 4 additional tension piles. The piles were tested up to 150% of their design capacities. Vibrating Wire Strain-Gauges were used for measuring the strains. The pile settlements were monitored at 1 minute intervals in order to produce the related load/time-displacement curve.

Figure 2. Pile test arrangement

PLT-1 and PLT-3 showed a total settlement of 7.89 mm and 11.36 mm for 10 000 kN load. For the last loading step, the settlement increased with 0.49 mm for PLT-1 and 0.71 mm for PLT-3 during the last 3 hours. So it has to be concluded that even after 6 hours loading, the stabilization of the settlements was not obtain.

The strain gauges showed large differences of the unit skin friction mobilized within the same soil layer for the different tests.

These differences clearly indicated that the mobilized unit skin friction is determined by the execution of pile. Normally, almost the same unit skin friction should be mobilized in a certain layer.

Based on these observation, the pile tests have been considered as failed.

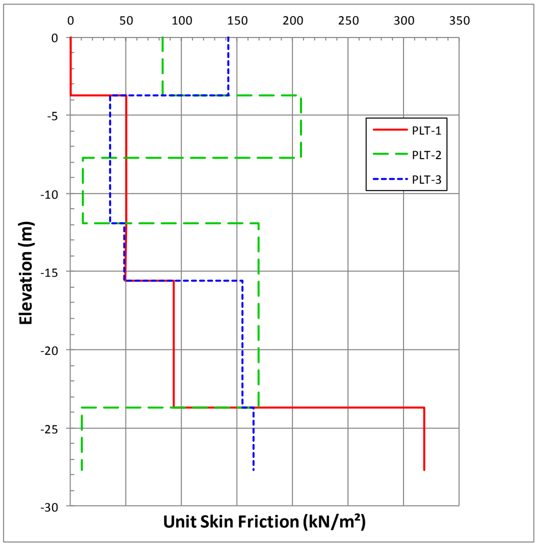

Figure 3. Measured unit skin friction

5 PILED SOLUTION

The initial foundation system was supporting the tower on larger bored piles anchored in the deep limestone layer (-31m). Due to the presence of the confined aquifer, execution of these piles became nearly impossible. After the test pile installation failure, it has been decided to design a piled solution with shorter piles to avoid drilling through the impervious layer. These piles have a bearing capacity developed by friction in the loam and clay layers. Their capacities is almost half of the 31 m ones. This pile arrangement implies piling layout modification and an increase of the expected settlements having implication on the structural design.

To manage the implication on the structure, sophisticated design approach are used to predict the settlement trough and improve the soil-structure interaction analysis.

6 STRUCTURAL

The weight of the superstructure is transferred to the soil by means of an 2.4 meter thick raft over the entire surface of the building. The raft is supported by 1.2 meter diameter bored piles with a length of 12.85m.

The structure is divided in 3 zones (building core, podium and basement) with different loading patterns. The spacing of the piles is variable. Under the most heavily loaded area a grid of 2.34m by 2.34m is foreseen while on the outer part a grid of 5.3m by 3.5m is used.

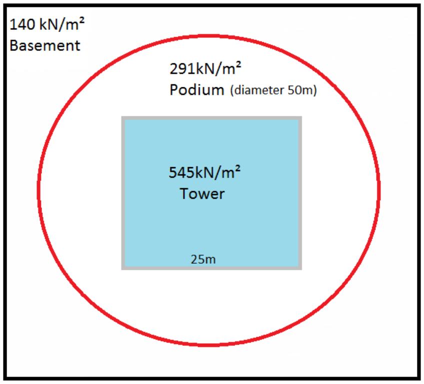

Figure 4. Load distribution under the tower

7 CALCULATION MODELS

7.1 Geotechnical model

The usual method to predict settlement trough (curve?) with short piles and supporting raft uses an equivalent raft analysis with loading of a fictive plate at 1/3 of the pile length in the bearing layer.

Settlement prediction has been performed using 2 different methods. To start a 2D finite element geotechnical calculation model has been used using the equivalent raft methodology. The equivalent plate stiffness has been estimated based on the full tower stiffness. This method did produce results with a reasonable accuracy. As the structure is symmetrical, half of a cross-section is considered in the 2D analysis

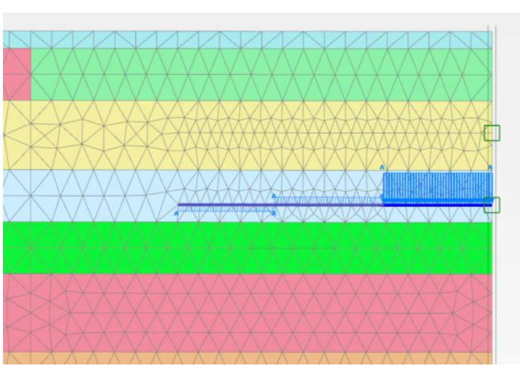

Figure 5. Plaxis 2D – Equivalent plate analysis

In a second stage, a 3D finite element geotechnical model has been constructed modelling all the piles and raft. In this model, both pile behavior and raft soil interaction are better considered.

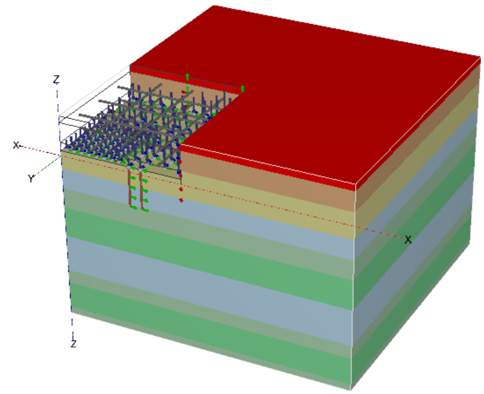

Figure 6. Plaxis 3D – Pile and raft

In the analysis, Hardening Soil Model is used with its related soil parameters. In the 3D analysis ¼ of the construction has been modeled due to the symmetry.

7.2 Structural model

The whole concrete structure has been modeled using the finite element software Scia. Elastic linear behavior has been considered for the structure and the piles are modelled by elastic springs. The outputs of the soil structure interaction analysis is used for the definition of the stiffness of each pile.

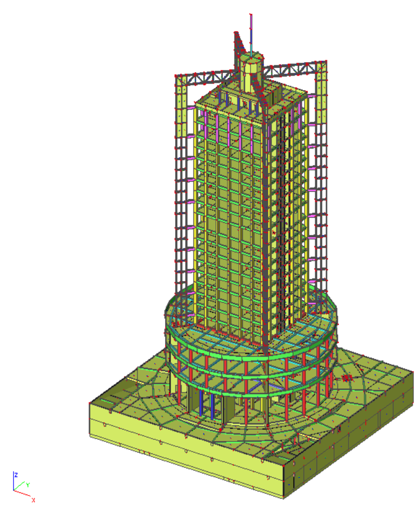

Figure 7. Structural Finite Element Model

7.3 Iteration process

In the first iteration, the loads extracted from the structural FE model calculated with uniform springs are introduced in the FE Geotechnical Model. Based on the calculated settlement in the geotechnical FE model and the introduced loads, revised springs stiffness to be used in the FE structural model are calculated. Iteration between the structural and the geotechnical model are performed until required accuracy has been reached in the shape and magnitude of the calculated deformations. The convergence has been reached in 3 iteration steps.

8 SETTLEMENT PREDICTION

The settlement prediction has been done with help of Plaxis 2D and 3D software.

The 2D analysis was not giving results within the expected accuracy and was overestimating the settlements which could lead to an overdesign of the structure.

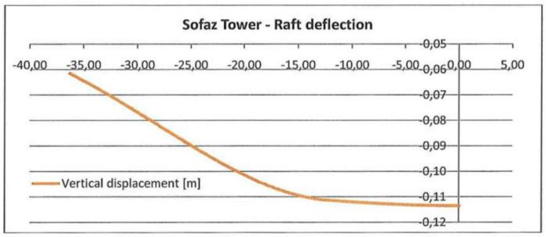

Figure 8. Predicted settlement from 2D analysis

The 3D analysis shows a different settlement trough which seemed to be more realistic.

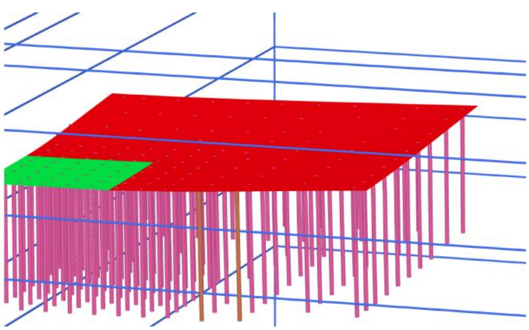

Figure 9. Plaxis 3D – Pile – Raft – Deformed shape

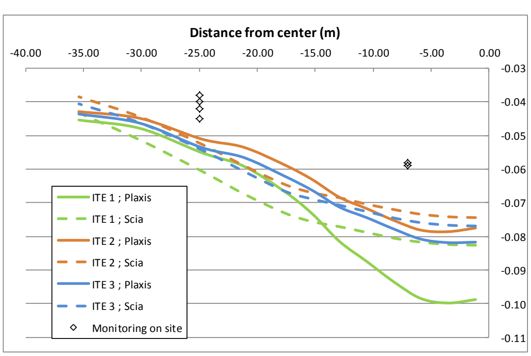

Figure 10. Predicted settlement from 3D analysis for the different iteration steps

9 SETTLEMENT MONITORING

During the construction of the tower, the level of 6 points situated at the ground floor were surveyed every month. The location of the points is given in Figure 9. Two points (point 5 and point 6) are situated at the corner of the core walls of the tower while the four other points (points 1, 2, 3 and 4) are at the edge of the podium. The aim was to define the absolute total settlement and the differential settlement between the center and the edge of the foundation raft.

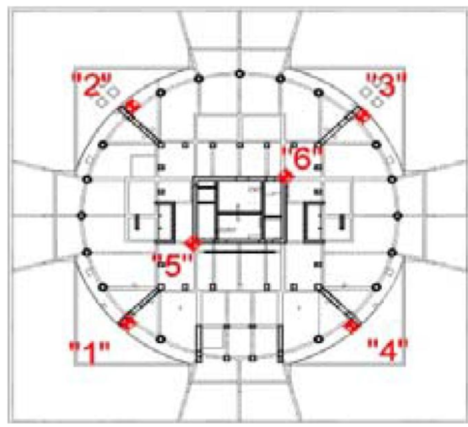

Figure 11. Settlement monitoring's points

The Figure 10 gives the evolution of the settlement during the construction of the tower. Concrete walls on the foundation raft were casted in November 2011(beginning of the graph). The end of the concrete works was in May 2013. The survey was continued until August 2014.

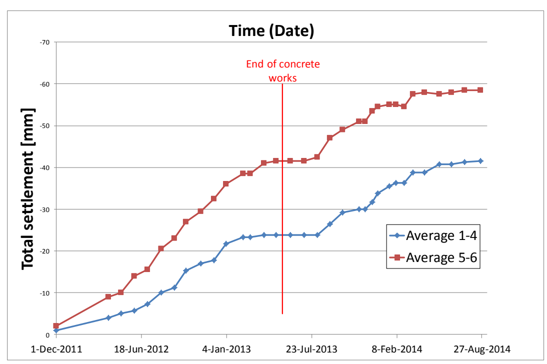

Figure 12. Settlement curves

The curves show a stabilization of the settlement at the end of the concrete works while finishing works were going on continuously. No explanation has been found for this horizontal part of the curve which happened between February and July 2013.

The maximum settlement (in August 2014) in the center is about 60 mm which is smaller than the long term estimated settlement which was 80mm.

The settlement at the edge of the podium is varying between 38 and 45mm. These values are smaller than the prediction which was about 50mm.

The maximum differential settlement is therefore about 20mm while the prediction was 30mm.

As the differential settlement induces a general bending of the basement and therefore additional internal forces in walls and slab, the FE model used for the design of the tower is well situated on the safe side. The differential settlement of 20mm is not the final value but it is not expected that the long term value will increase up to 30mm.

10 CONCLUSION

Piles of the Sofaz tower are mainly embedded in relatively soft layers and their end bearing capacity is rather small. Considering the same stiffness for every pile would have led to an overestimation of the pile reaction forces under the tower and an underestimation of the reaction forces under the podium part. General ground settlement has to be considered to define the additional internal forces in the basement (walls columns and slabs) due to the differential settlement between the center and the edge of the foundation. A soil structure interaction analysis was performed using a geotechnical FEM program Plaxis to simulate the interaction between raft-pile and soil, and a structural 3D model in which the piles are modelled as uncoupled springs. Both program were used in turn until convergence of pile head settlement in both was obtained.

The survey of the settlement performed during the construction of the tower gives a total settlement of 60mm while the estimation was 80mm. The surveyed differential settlement of the foundation is less than the prediction which validates the structural model that has been used for the design of the concrete elements.