Barretted raft design for high-rise building applying 3D numerical tool

Le projet du fondement tabulaire-barrette d'un gratte-ciel en appliquant un modèle numérique 3D

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ABSTRACT

Geotechnical design process of a barretted raft foundation for a high-rise building in Warsaw is presented with the emphasis on comprehensive site and laboratory investigation allowing for precise assessment of geotechnical design parameters. The new development is being constructed at the location of former structure comprising two level basement surrounded by diaphragm walls along the site perimeter. The existing diaphragm walls and part of the original foundation raft are re-used in the new foundation scheme with new foundation raft cast onto the remaining section of the former one. Barrettes are designed as settlement reducing members below the core of the structure with application of base pre-stressing. The ground profile comprises made ground, two series of boulder clays underlain by a very dense sandy formation resting upon Tertiary subsoil represented by high plasticity clays. Soil-structure interaction analysis of the entire foundation system with application of 3D numerical analysis is described and results analysed. A thesis is formulated that adequately utilised sophisticated analysis methods when supported by high quality geotechnical investigation may lead to time and cost savings during the design process. Such sophisticated approach utilising numerical methods shall become a standard approach for types of development like high rise buildings, complicated and deep excavations, tunnels.

RÉSUMÉ

Dans cet article nous avons présenté les étapes du projet géotechnique du fondement tabulaire-barrette d'un gratte-ciel en mettant l'accent sur la nécessité des analyses régulières du terrain ainsi que celles au laboratoire. Elles permettront de mesurer les paramètres géotechniques de façon efficace. Le bâtiment dont on a fait le projet va être situé à la place d'un bâtiment de deux étages de sous-sol entourés de diaphragmes situés le long du terrain. Ces diaphragmes ainsi qu'une partie de l'empoise vont être utilisés pour élever un nouveau bâtiment. Les barrettes du fondement serviront d'éléments permettant de diminuer le tassement. Le sol se compose de plusieurs couches (argile, sable condensé, argile tertiaire). Nous avons aussi décrit l'analyse des dépendances de la construction du sous-sol en appliquant les méthodes numériques. Enfin, nous avons présenté la thèse soulignant l'importance de l'application des méthodes pointues et des données géotechniques de qualité supérieure dans la création d'un projet géotechnique. L'application des méthodes numériques devrait devenir un pratique régulière dans les travaux sur les projets des constructions d'un niveau de difficulté très élevé.

Keywords : High-rise building, foundation design, barretted raft, numerical analysis, finite element method

1 INTRODUCTION

This paper discusses the most important foundation design aspects of a high-rise building in Warsaw City centre. The main idea of this document is to present the not stereotyped design approach resulting from the size, character and complexity of the structure, which is often not reflected by local standards in force. Among other the following issues are discussed: advanced geotechnical investigation and laboratory testing and finally the 3-dimensional numerical analysis of soil-structure interaction with application of finite element method (FEM).

2 PROJECT SETTINGS

2.1 *Site location and characteristics*

The site of the planned high-rise building is located in the Warsaw City centre at 44 Złota Street in the place of a demolished 6-storey structure (see Figure 1 below).

In the close vicinity of the site there are located Holiday Inn hotel (to the west), Warsaw Towers Office building (to the north), residential blocks (to the north and east) and finally one of the largest mixed used developments in Warsaw „Golden Terraces" with the Main Railway Station immediately behind (to the south). Besides, the iconic structure of the Palace of Science and Culture is located approximately 150m to the east from the site boundaries.

The presence, importance and sensitivity of the adjacent structures has been of paramount importance from architectural, structural and geotechnical design points of view, as the influence of the new development on the neighbouring developments had to be minimised.

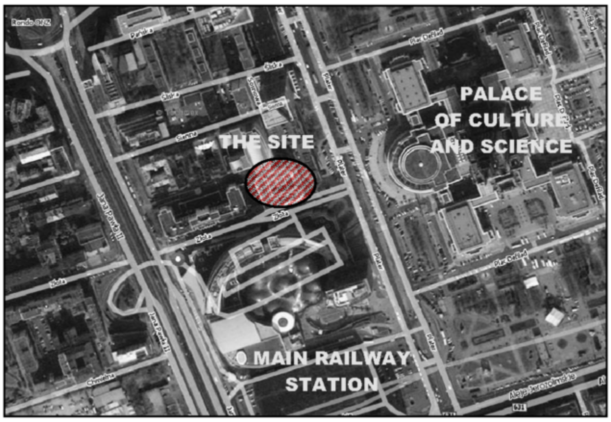

Figure 1. Site location of the designed structure.

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2.2 *Designed structure*

The designed structure shall comprise 54 above the ground stories and two levels of basement with the total height of the building equal to 192m. The area covered by the development equals 2900 m^2.

The underground section of the building comprises two stories embedded into the existing diaphragm walls. The foundation of the structure has been designed as a barretted raft, with the barrettes localised within the core area axially beneath the columns and the core walls. The lower 6 stories are forming a podium with car park and commercial areas, while the remaining stories are forming a residential tower with the apartments having variable area owing to the irregular shape of the building.

The structural system of the building is based on a central core with supporting shear walls. The building stability is ascertained by the core itself, lifts and services shafts as well as by the external shear walls connected with the core by three rows of "link-beams". Figure 2 below is showing the schematic view of the building.

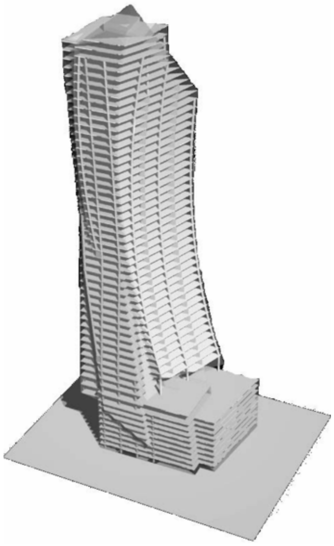

Figure 2. Schematic presentation of the analysed structure.

3 GEOTECHNICAL SETTINGS

3.1 *Desk studies*

During the first stage of geotechnical assessment archival data were collated in connection with both the subsoil and the existing structure to allow identification of major risks and to enable targeted ground investigation design.

The conducted desk studies proved to be very valuable source of information for subsequent design stages. A generalised ground model has been elaborated and information on foundations of existing structure and neighbouring buildings were collected. The results of the desk studies strongly influenced the approach for foundation design concept, especially in connection with the potential for re-use of selected parts of the existing foundation system (of the structure to be demolished).

It is concluded that the importance of the desk studies can not be underestimated as there are significant benefits arisings from early identification of potential risks. This conclusion is especially valid for any developments within urban areas, where issues as existing foundations, neighbouring buildings, Made Ground presence and for example contamination may strongly influence the design.

3.2 *Ground investigation*

The ground investigation for the needs of the analysed project was conducted in autumn-winter 2005 by a local contractor Geoteko Ltd from Warsaw based on specification prepared by the author of this paper.

It is worth underlining that the vast majority of the works was executed from the lower basement level of the existing building, which has been in operation during that period and many limitations applied, including headroom of 2.7m only. This required utilisation of special rigs to perform the works and caused difficulties with adequate soil sampling (especially undisturbed sampling).

The ground investigation comprised execution of the following works:

- 7 boreholes to the depth of 50m from the site level outside the existing building (4) and basement level inside the building (3);
- 9 cone penetration tests to maximum depth of 24.5m from the site level outside the existing building (3) and basement level inside the building (6);

It is stressed that the final scope of works deviated from the originally designed one, due to technical difficulties and ground conditions encountered. The main issue, was the density ratio of the sandy and gravelly stratum, resulting in CPT rig not being able to penetrate this material. The other crucial issue from the design point of view was the potential presence of clayey interlayers within the sand formation (not exceeding 1m in thickness) – as it was not possible to determine this with adequate certainty (boreholes inside the building were drilled with application of rotary coring technique with water flush due to headroom limitation), additional 7 boreholes were scheduled to follow the demolition of existing building (in November 2007).

One of the most important elements of the geotechnical assessment for the design needs was adequate scheduling of laboratory testing.

First reason for that was to obtain realistic geotechnical parameters of soils stiffness (especially in terms of small strain stiffness), as it was meant to be one of the governing factors to affect the foundation design. Utilisation of geotechnical parameters imposed by local standards that is common practice in foundation design as is observed by the author or based on limited amount of standard laboratory tests could have led to overestimation of settlement and in turn significant over-design.

Secondly, if a 3D numerical analysis was to be introduced, then definition of most accurate parameters had been inevitable, otherwise the FEM analysis would not have sound basis and the outcome could have been far from realistic. Use of other than most direct methods available for defining the geotechnical parameters for a chosen constitutive model shall be limited and carefully considered.

In the light of the above assumptions, the following (advanced) laboratory analyses were carried out, apart from the standard ones comprising index properties, basic strength and stiffness tests, etc:

- iso- and anisotropic triaxial consolidated drained tests (TXCID/TXCAD) on reconstituted samples of granular material (sands and gravels) within broad range of stresses and for three different density ratios;

- isotropic triaxial consolidated drained and undrained tests (TXCID/TXCIU) on soil samples from cohesive strata encountered, within broad range of stresses;

- shear wave velocity measurements at low level strains during consolidation in the above tests to quantify the initial stiffness characteristics.

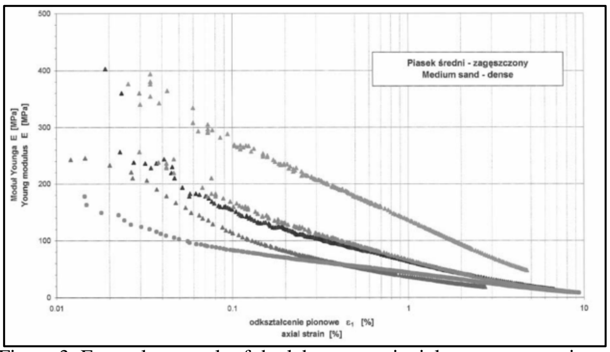

Figure 3. Exemplary result of the laboratory triaxial test on reconstituted samples of sand.

An example of the laboratory test results is presented in Figure 3 above where the distribution of Young Modulus versus strain is shown for a reconstituted sample of sand with a density ratio value of 90%.

3.3 *Geological structure and geotechnical conditions*

3.3.1 *Geological sequence*

The subsoil of the investment site is generally in line with what could be expected for the area for the centre of Warsaw. Beneath a few metres thickness of inhomogeneous Made Ground and local sandy and cohesive layers of lacustrine origin there are present two series of glacial Boulders Clays represented by sandy clays in a stiff to very stiff condition. The Boulder Clays are underlain by very dense interglacial Sands and Gravels, which were already mentioned above in this paper. This formation is in turn underlain by Tertiary Clays, which were encountered in the form of high plasticity clays in a firm to stiff and very stiff consistency. The top of this stratum is present approximately between 38 and 47 metres below ground level.

In general the soil layering is horizontal and for the needs of the design four major geotechnical units were determined as presented below in Figure 4. The units are as follows: Upper Boulder Clays, Lower Boulder Clays, Sands and Gravels, Tertiary Clays.

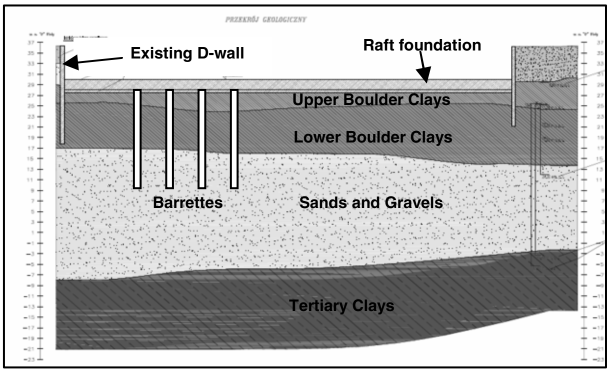

Figure 4. Generalised geotechnical cross-section running east-west.

3.3.2 *Hydrogeological settings*

Three independent groundwater horizons were identified within the subsoil of the analysed area. The first two are of Quaternary character and the third one is associated with Tertiary soils (ignored in this article as not relevant).

The upper horizon is connected with the subsurface deposits and has got a free groundwater table stabilising approximately 6m bgl. The groundwater of this horizon has no connectivity with the layers below due to isolation by Boulder Clay series.

The second Quaternary groundwater horizon is associated with the interglacial Sands and Gravels. It is of tight character and stabilises at a depth of approximately 10.5 bgl, which is corresponding with a depth of 2 metres below the foundation level. A long-term monitoring of standpipes installed within this horizon has shown no major fluctuation of the groundwater table (it did not exceeded ± 30-40cm).

3.3.3 *Geotechnical design parameters*

As can be seen in Figure 4 above the foundation level of the proposed structure is entirely present within the Upper Boulder Clays formation, while the toes of the barrettes supporting the raft in core area are founded within the very dense Sands and Gravels.

Considering the over viewing character of this paper, the detailed geotechnical analysis of design parameters selection can not be fully described herein, but in order to enable the reader to familiarise himself with the specific conditions the geotechnical parameters finally adopted in the analysis are presented in the Table 1 below. To prove the statement made in section 3.2 about need to derive realistic parameters the last column of the table shows stiffness moduli values imposed by relevant national standard (PKN, 1981) for comparison.

Table 1. Geotechnical design parameters for the foundation analysis.

Geotechnical layer	C, kN/m^2	ϕ, degrees	E, MN/m^2	E increase MN/m^2/m	K_0	E_{ref}[1)], MN/m^2
Upper Boulder Clays	5	32	60	-	1.0	50
Lower Boulder Clays	4	35	120	-	1.2	67
Sands and Gravels	0	42	400	5	0.7	180
Tertiary Clays	13	22	150	10	1.2	23

[1)] – values of Young Modulus if derived from national standard

4 FOUNDATION ANALYSIS

4.1 *Design assumptions*

As the entire design effort has been split between offices in Poland and USA it was of paramount importance to decide on the standards to be adopted. During the concept design stage, which took place in New York, Polish standards for loads and structural design were implemented to avoid confusion and difficulties at subsequent design stages in Poland. This was especially relevant for snow and wind loading of the structure.

For the needs of the design wind tunnel investigation was realised in CPP (Colorado, USA), which analysis results were utilised during further design stages. The model prepared for the wind tunnel test is shown in Figure 5 below.

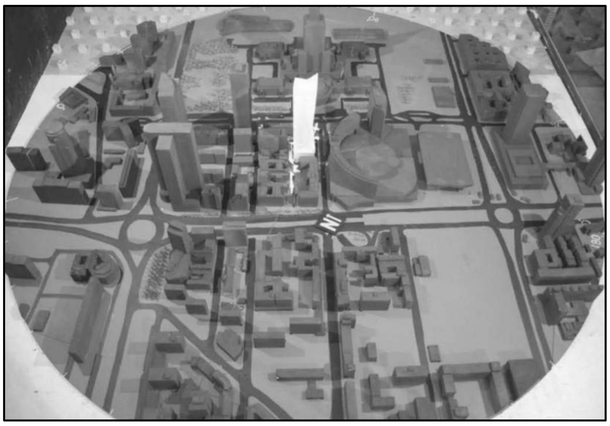

Figure 5. The model of the area for the needs of wind tunnel testing.

There were following initial options of foundation system analysed at the early stages of the project:

- new structure outside existing diaphragm wall with 4 levels of basement; abandoned due to proximity of dense network of utilities and neighbouring buildings;
- simple foundation raft; option abandoned as the expected raft thickness of 3.5m would minimise the headroom for basement levels;
- piled foundation based on a number of approximately 120 large diameter piles, which finally evolved into a barretted foundation raft, with 42 barrettes with pre-stressed bases (2.8x0.8m) and two zones of the raft

itself (2.05m thick below the core and 1.5m thick elsewhere within the footprint).

4.2 *Analysis methods*

The first part of the foundation analysis was based on structural approach (and software), where soils were modelled with springs and bi-linear characteristics were used to model the barrettes. Such simplification allowed assessing the range of settlement and related reaction on the foundation system. This has been used to optimise the foundation system, mainly number and location of the barrettes.

The values of the stiffness of the springs were based on settlement calculations with application of simple linear elastic model of the subsoil. Following a number of iterations to obtain a reliable relationship between the load and settlement final values were reached. The load-settlement characteristics for the barrettes were obtained by calculating barrettes load capacity with application of effective stress approach (Tomlinson 1994).

At the final stage of the design (during detailed design) it has been decided to carry out an advanced soil-structure analysis with application of finite element method. The purpose of this analysis was to optimise the design and to enable better understanding whether the entire foundation system actually behaves as a barretted raft..

4.3 *Finite Element Method (3D) Application*

For the needs of the analysis Midas GTS software was used and basing on the results of the ground investigation and subsequent assessment of soil conditions Coulomb-Mohr constitutive model was adopted for the needs of the analysis.

The main aim of the analysis was to estimate the settlement of the structure and the internal forces within the foundation elements as the raft and barrettes basing on the interaction between the soil and the structure. All the calculations were executed in fully drained conditions. Very important element of the analysis from its correctness point of view was appropriate definition of the subsequent construction stages from stress initialisation, through reflecting the post-demolition condition, foundation execution to loading stages.

It is also important to underline that both barrettes and the foundation raft were model as solid elements with real thickness, while diaphragm walls and structural members forming the basement were modelled as plates and beams.

The analysis undertaken led to the following observations:

- the results of soil-structure analysis allow for much more detailed and comprehensive understanding of the entire foundation system behaviour together with surrounding soils than standard methods used by structural engineers, however great care should be taken while interpreting the results in the light of assumptions and simplifications made;
- the decision between using short-term or long-term concrete stiffness had significant impact on the final results (long-term stiffness utilisation is recommended);
- internal forces in the raft obtained during the analysis were somewhat in excess of those not accounting for soil-structure interaction, what resulted in local increase of reinforcement within the raft;
- the numerical analysis is indicating higher proportion of load to be taken by the barrettes than the raft compared to former analyses, while the load distribution along the barrettes and their load capacity are in line with the basic geotechnical calculations carried out initially.

Below in Figure 6 the obtained settlement results are presented, which indicate 5 to 6 cm of settlement below the building core decreasing to approximately 1 to 2 cm along the building perimeter. It is noted that at the time of writing this paper there were approximately 15 stories completed (self-weight only) and the observed settlement did not exceed 10mm.

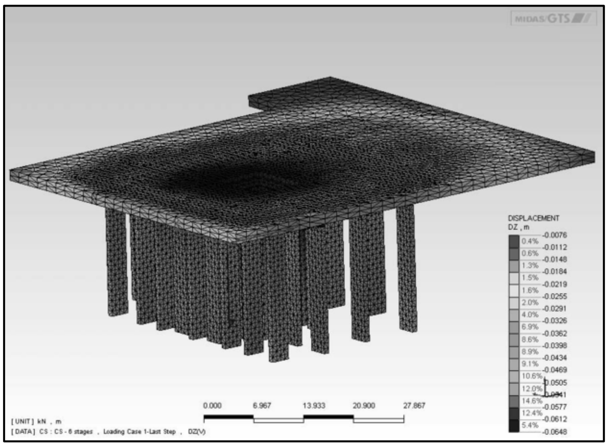

Figure 6. Foundation settlement as example of the numerical analysis results.

5 CONCLUSIONS

There are two major aspects considered beneficial from foundation point of view: comprehensive desk studies further activities driver and detailed site laboratory investigation enabling to define realistic geotechnical design parameters. Without precise assessment of geotechnical parameters, selection of appropriate constitutive model for the needs of subsequent numerical analysis of soil-structure interaction would be difficult and the results could be easily misleading.

The author of this document is convinced that the design approach in connection with relatively complex structure, that is presented in this paper together with high level of close cooperation between structural and geotechnical engineers are setting a good example for similar design problems in future.

It can also be concluded that application of 3D numerical analysis of soil-structure interaction for complex structures or ground conditions in urban areas shall be gradually becoming standardised procedure in design. Nevertheless, care should be taken when making decisions regarding modelling strategy, selection of constitutive models, design parameters and the aim of the very analysis, as the answers obtained with such design tool are clearly depending on the reliability of the input data.

Additionally it is of paramount importance to monitor the behaviour of the completed structures to allow a future back analysis, which should shed more light on the correctness of the parameters used in the design.

Finally, it is firmly believed that the selection of piled or barretted raft solutions for high-rise buildings is the most adequate one, also from sustainability point of view, if the economic benefits and the reduction in raw material usage for the foundation system are taken into account.

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