Proceedings of the XVII ECSMGE-2019
Geotechnical Engineering foundation of the future
ISBN 978-9935-9436-1-3
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doi: 10.32075/17ECSMGE-2019-0850

XVII European Conference
ECSMGE 2019
Reykjavik
on Soil Mechanics
and Geotechnical Engineering

An analysis of the foundations of the highest building in EU based on numerical modelling and pile load test

Une analyse des fondations du plus haut bâtiment de l'UE basée sur la modélisation numérique et un essai de chargement des pieux

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ABSTRACT: The paper contains the results and the conclusions of a complex 3D FEM analysis of the foundation of the tallest building in the European Union made in ARSA and ZSoil. ARSA environment was used to build a spatial model to estimate the load acting on piled-raft foundation. An analogical 3D model limited to the underground part of the designed building was created in ZSoil to define a proper soil-structure interaction. The obtained stiffness of barrettes as well as of ground beneath the raft were implemented in ARSA. In the framework of the design process two in-situ barrette load tests were performed up to 23 MN. Rows of extensometer sensors were installed along the entire length of the barrettes to measure the distribution of the axial force. To calibrate soil parameters in ZSoil HSs model, the authors based their approach on the load-settlement ratio and the axial force distribution in the examined in the field and the modelled barrettes. Relevant soil and interface parameters were adopted. Finally, the convergence of sharing of load in the elements of piled-raft foundation as well as the settlement of foundation slab allowed the designers to correctly design the whole structure.

RÉSUMÉ: Le document contient les résultats et les conclusions d'une analyse complexe 3D MEF des fondations du plus haut bâtiment de l'Union européenne, réalisée en ARSA et ZSoil. Le logiciel ARSA a été utilisé pour réaliser un modèle 3D permettant d'évaluer les chargent qui s'exercent sur le radier de fondation sur pieux. Un modèle 3D analogique mais limité à la partie souterraine du bâtiment a été conçu dans ZSoil pour définir une interaction sol-structure adéquate. Les résultats de rigidité des barrettes ainsi que du sol sous le radier ont été saisis dans le logiciel ARSA. Dans le cadre des études de conception, deux essais de charge in situ de chargement des barrettes ont été effectués jusqu'au niveau de 23 MN. Des rangées de capteurs extensométriques ont été installées sur toute la longueur des barrettes pour mesurer la répartition de la force axiale. Afin de calibrer les paramètres de sol dans le modèle ZSoil HSs, les auteurs se sont appuyés sur la relation entre le tassement et la charge ainsi que sur la répartition de la charge axiale dans les barrettes testées sur le terrain et modélisées numériquement. A l'issu du paramétrage les valeurs de sol et d'interface pertinentes ont été retenues. Enfin, la convergence de la répartition de la charge dans les éléments du radier sur pieux ainsi que le tassement de la dalle de fondation ont permis aux concepteurs de réaliser un projet correct de l'ensemble de la structure.

Keywords: Combined pile-raft foundation, static load test, structure stiffness, 3D FEM analysis

1 INTRODUCTION

Almost all types of deep foundations are used in the foundations of high-rise buildings. A commonly used economical approach is the use of combined pile raft foundations - CPRF in the diaphragm wall technology. CPRF transfers a part of the working load directly to the ground under the raft and the remaining part of the load is transferred to the piles. However, the system settles as a whole. The incorporation of piles to the slab's interaction with the soil results in a reduction of settlement by skin friction and pile tip resistance. The problem is to take into account the strongly non-linear and complex phenomena occurring in the interaction of the structure with the ground which has a significant impact on the load bearing capacity of the elements of the entire system. Such factors include interactions of the pile group, the slab and the soil (Katzenbach, Lepla, 2015).

The purpose of this study is to provide a comprehensive numerical analysis based on the example of designing the foundation of the highest building in the European Union in soil conditions typical for Warsaw, described in detail in (Kacprzak, Bodus, 2018). The analysis was carried out on the basis of a 3D numerical model of the underground part created in the ZSoil programme in cooperation with a model from Autodesk Robot Structural Analysis (ARSA). The analysis uses a work algorithm (Kacprzak, Bodus, 2018) showing the possibility of cooperation between the two mentioned tools using FEM. The correctness of the assumptions of the soil model parameters was verified using in-situ barrette loading tests. By making spatial models of the static load test, a convergence of the load-settlement curves of the tested barrettes was obtained.

2 STRUCTURAL ANALYSIS

The static diagram of each high-rise building is compared to the operation of a bracket. For this reason, a correct anchorage must be provided. That is why underground floors are always designed, often in the form of a foundation box. The number of underground floors usually depends on the height of the building and its functions.

The designed building will consist of four underground levels and fifty two levels above the ground level. The overall height of the building is 310 m including an 80-metre mast. The building will contain office spaces and retail premises.

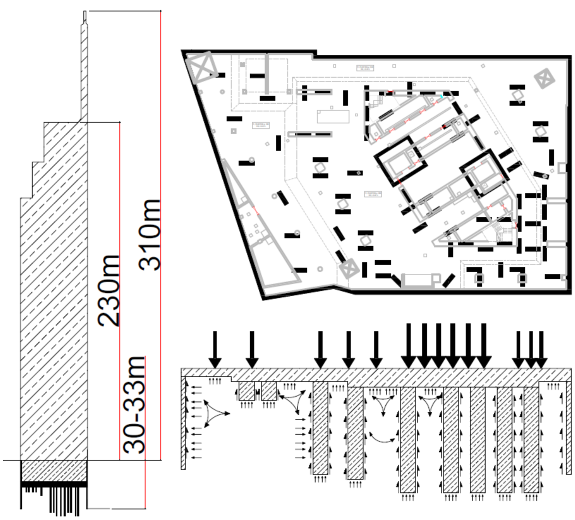

Figure 1. Geometry of the building, CPRF with the structures core and diagram of pile-soil-structure interaction

Static calculations of the discussed building were made in the Autodesk Robot Structural Analysis programme (ARSA) for the underground model previously created in ARSA. A properly collected system of reaction forces was directly imported and applied to the foundation slab in the three-dimensional ZSoil underground model. The mechanical parameters of the soil models were calibrated using the results of the barrette load tests. In this analysis, the block diagram presented in (Kacprzak, Bodus, 2018) has been expanded and shown in Figure 2.

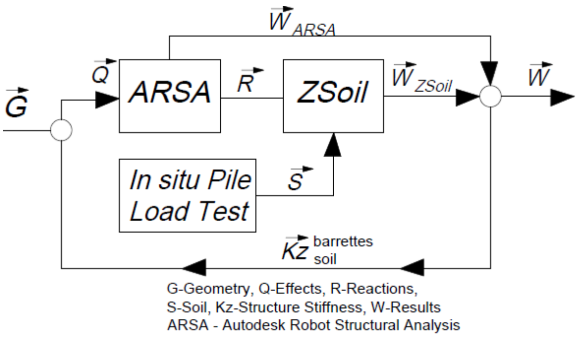

Figure 2. Simplified block diagram of the complex analysis

2.1 Barrette load test

Static Load Test (SLT) is an in-situ type of load testing used in geotechnical investigation to determine the bearing capacity of deep foundations prior to the construction of a building. At the design stage, static load tests were performed on barrettes with a cross-section of 280 x 80 cm and a length of approximately 28 m and 34 m. The paper describes the test of a 34-metre long barrette (barrette B82). The barrette test was performed using the traditional anchoring method. Anchor barrettes were set crosswise to barette-B82. The loading structure consisted of a main beam anchored to four adjacent barrettes. Lengths of the anchor barrettes were chosen by assuming a transfer by a single barrette of 1/4 of the load value. Figure 3 shows the loading structure during the test (Kacprzak, Bodus, 2018).

Figure 3. Structure of barrette load test - Barrette B82

In the first 10 meters the soil was disturbed in order to weaken the skin friction resistance of the barrette - as a lack of cooperation with the ground base after making the excavation. In addition, a line of extensometer sensors was placed inside the barrette to determine the course of the axial force. The obtained results served as a basis for verification of the computational models used in further analysis.

The computational model of the examined barrette consisted in the creation of a soil medium with dimensions of 21 x 21 x 56 m with boundary conditions on the external surfaces of the medium. The finite element mesh division was adopted at the level of 0.5 - 1.0 m. The ground base was modelled using 3D continuum elements with the parameters of the Coulomb-Mohr model (C-M) and the Hardening Soil model with Small Strain Stiffness (HSs). The soil which was actually disturbed was weakened which reduced the resistance of the barrette skin friction by reducing the mechanical parameters of the soil along the first 10 metres. In the so-formed ground base a test barrette was embedded along with anchor barrettes. The tested barrette was loaded with the same force as actually estimated in accordance with a design of the Road and Bridge Research Institute. Barrettes with dimensions of 2.8 x 0.8 m were modelled using beam-type elements (piles embedded) with a 0.95 m circular cross-section, spaced at 1.0 m intervals, which gives a good approximation of the actual barrette. In the model test 1/3 of the value of the loading force was assumed for a single beam element. The same assumption was made for the anchoring barrettes, i.e. it was assumed that each anchoring barrette would accept 1/4 of the applied force, i.e. 1/12 for each beam element. Figure 4 shows a view from the computational model with the adopted layer distribution. Figure 5 presents a test barrette with anchoring barrettes and a layer of weakened soil.

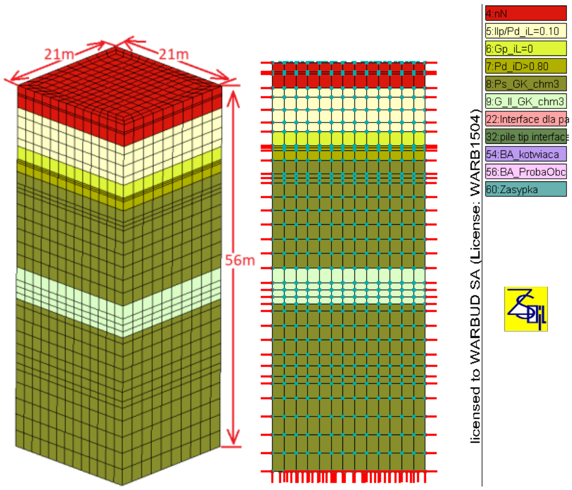

Figure 4. View of the 3D model of the barrette load testing

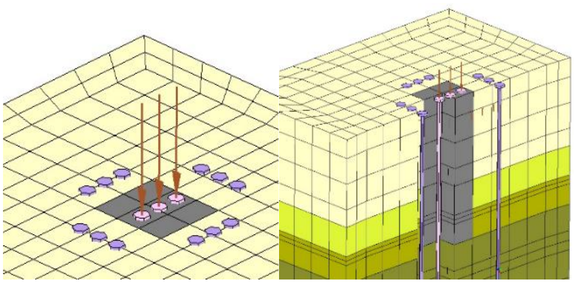

Figure 5. View of barrette B82 layout, anchor barrettes and the weakened soil layer in the ZSoil model

Figure 6 shows the results obtained in static load test and 3D FEM analysis . The results are presented in the form of load-settlement curves. Barrette behavior was in the elastic region. Figure 7 shows the distribution of axial force over the entire length of the tested barrette. The results are presented for chosen values of the applied load.

Calibration of the results of the modelled and the static load test consisted, in selecting appropriate parameters of the friction interface in the contact of the barrette with the subsoil. Table 1 shows the adopted values. The unitary coefficient of the tangent value of the internal friction angle, cohesion and tangent of the dilatancy angle was assumed for all soils existing in the model, except the backfill, for which a reduction to the value of 0.75 was proposed.

After obtaining compatibility of the results of field and model tests, the parameters of the soil HSS model were implemented in a full 3D model of the designed building. Table 2 presents parameter values for sand and clay.

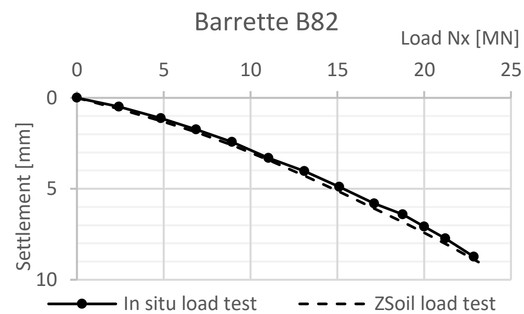

Figure 6. Load-settlement response of the head of the barrette under axial force from in-situ test and ZSoil model

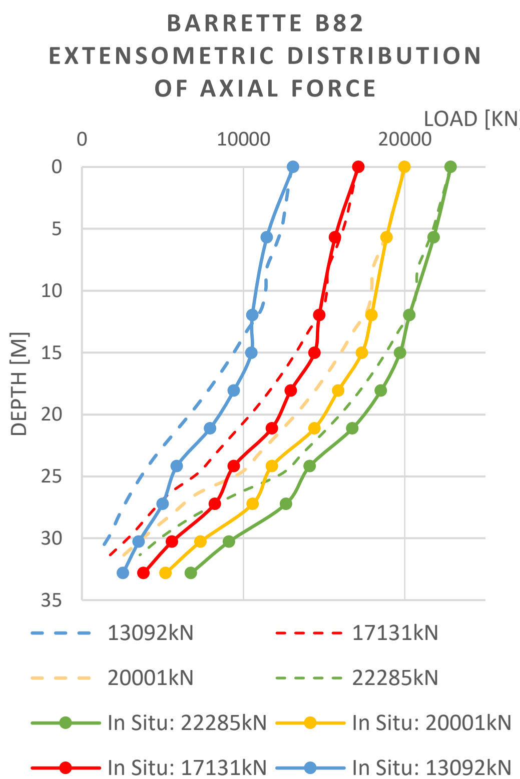

Figure 7. Distribution of axial force in barrette B82 from in situ test and ZSoil model

Table 1. Interface parameters in ZSoil model

Interface parameters							
$K_n multiplier$	K_n/K_t	$tg\phi$	c	$tg\psi$	Material	ϕ	c
0.1	1	1	1	1	Soil in model	ϕ in model	c in model
0.1	1	0.75	0.75	0.75	Backfill	13	10

Table 2. Design parameters of soil HSs model

Material parameters of sand													
E_{ur}^{ref}	ν_{ur}	m	σ_L	E_0^{ref}	$\gamma_{0.7}$	E_{50}^{ref}	σ_{ref}	Φ	Ψ	c'	E_{oed}	σ_{oed}^{ref}	K_0^{NC}
$[MPa]$	$[-]$	$[-]$	$[kPa]$	$[MPa]$	$[-]$	$[MPa]$	$[kPa]$	$[\ ^o]$	$[\ ^o]$	$[-]$	$[MPa]$	$[kPa]$	$[-]$
325	0.2	0.5	10	960	$1 \cdot 10^{-4}$	110	100	42.5	12.5	0.1	110	251	0.40
Material parameters of clay													
90	0.25	0.85	10	275	$2 \cdot 10^{-4}$	30	100	38	13	18	30	260	0.38

2.2 Implemented stiffness data

After validation of numerical models of barrette load test, soil and interface parameters were implemented in the underground model of the analysed building. A 3D view of the underground model from the ZSoil programme is shown in Figure 8.

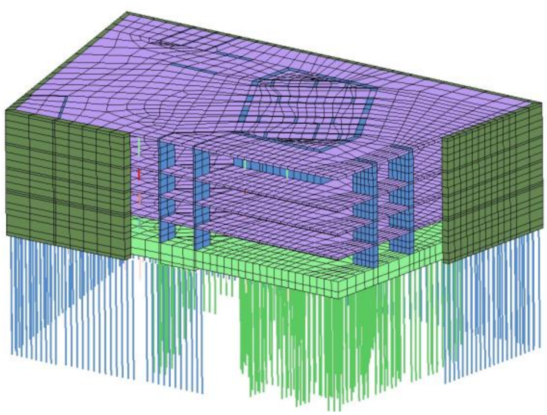

Figure 8. 3D view the underground part of the construction - diaphragm walls, slabs, cores, foundation slabs, barrettes

After 3D FEM calculations in ZSoil, the stiffness of the piled raft foundation was obtained. Barrette stiffness values were determined as the ratio of the working load in the barrette head to settlement. The ground stiffness under the foundation slab was determined as the quotient of the stress under the slab to foundation settlement.

Figure 9 shows the load vs. settlement curve for barrette in the piled raft system from the ZSoil model. The view of the ground stiffness map under the foundation slab is shown in Figure 10.

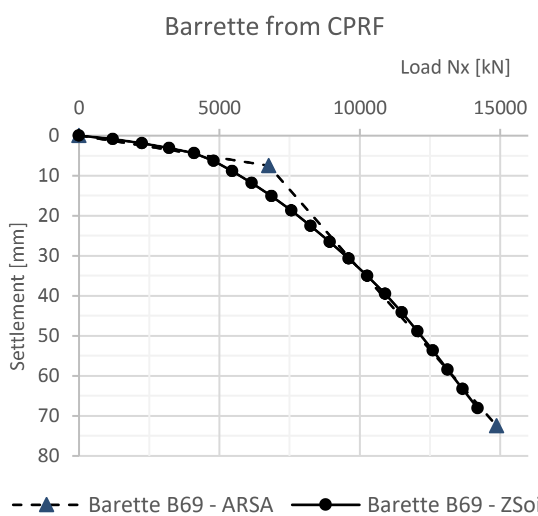

Figure 9. Load-settlement curve for barrette in CPRF in 3D ZSoil model with bilinear curve in ARSA model

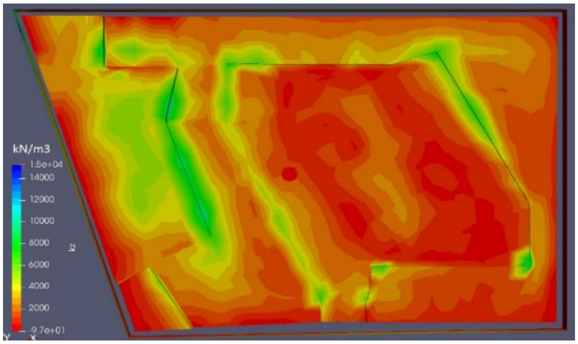

Figure 10. Ground stiffness under the foundation slab

Several barrette groups with similar location, length and curve character were chosen. By defining the obtained load-settlement relationships, e.g. in the bilinear way, the obtained curves can be introduced to the model in ARSA (Figure 11).

The soil stiffness under the foundation slab in ARSA is defined as a coefficient of elasticity k_z[kN/m^3] (Winkler soil elasticity coefficient) when setting parameters of calculation panels at the foundation slab modeling stage (Figure 12).

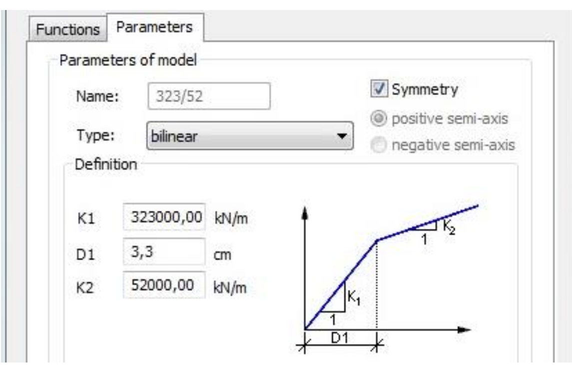

Figure 11. Support definition with nonlinear model in ARSA

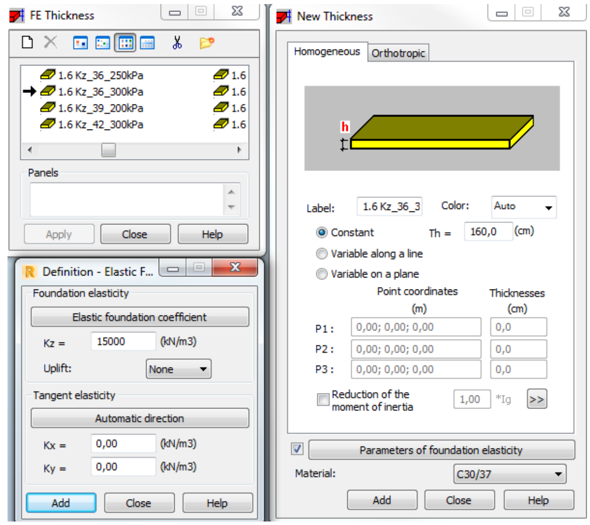

Figure 12. Definition of an elasticity modulus of the soil in ARSA

3 ANALYSIS OF THE RESULTS

The main result of the analysis is the consistency of results between programs. It is necessary to correctly defined the cooperation of the piled raft foundation with the ground base (interactions soil-piles-raft) in the ARSA model. Correct estimation of the load distribution in the CPRF components. The FEM analysis of the load distribution is shown in paper (Kacprzak, Bodus, 2018) and experimentally (Mandolini, G.Russo, C.Viggiani, 2005).

The correctness of the performed calculations is conditioned by the fulfilment of two basic criteria. The deformation criterion consists in the compatibility of the foundation deformation in ARSA and ZSoil. Figure 13 shows the foundation slab settlement map obtained in ZSoil. Maximum settlements occur in the high part, in the area of structural cores and reach the value of 5.40 cm. Figure 14 shows the slab settlement map in the ARSA. Settlement results were similar in that case. The largest settlement value occurs in the high-rise part of the building in the area of accumulation of the largest forces acting on the piled raft system.

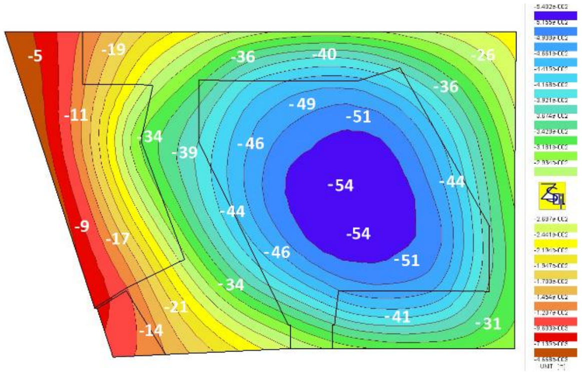

Figure 13. The settlement map of the foundation slab in ZSoil model [mm]

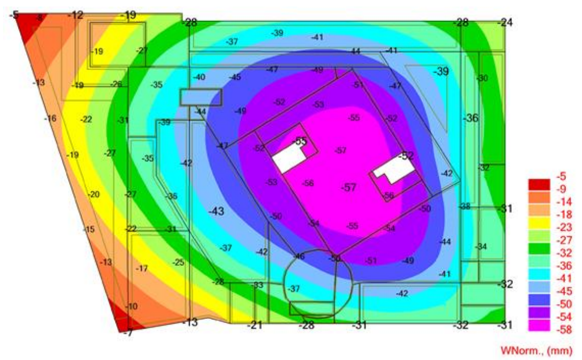

Figure 14. The settlement map of the foundation slab in ARSA model [mm]

The second condition for compliance is the stress criterion. A comparison of results between the ZSoil and ARSA models consists in obtaining identical reactions occurring in the barrette heads and in the compliance of the stresses occurring under the foundation slab. In order to meet this criterion, another iteration of the implementation of results between the models is carried out in accordance with the block diagram shown in Figure 2. With defined subsoil in the ARSA model, a map of soil reactions under the foundation slab and forces in the barrettes should be made. This load distribution should be imported into the ZSoil model. After performing calculations we proceed to compare the load distribution between the programs.

4 CONCLUSION

The complex analysis of the foundation of the high-rise building was carried out in a comprehensive manner. The correctness of the assumed assumptions of the soil model parameters was verified using field barrette loading tests. By making spatial models of the FEM static load test, a convergence of the load-settlement curves of the tested barrettes was obtained.

Based on the implementation of the ground base model taking into account all mutual interactions (raft-barrettes-soil) along with barrettes working as CPRF elements, the structural engineer is able to correctly design the whole building structure.

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