

Analysis of the soil-structure interaction of a high-rise building near sensitive infrastructures

Analyse de l'interaction sol-structure d'un immeuble de grande hauteur à proximité d'infrastructures sensibles

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ABSTRACT: As a consequence of the growing population in urban areas even high-rise buildings have to be planned near existing sensitive infrastructures. In the east of Frankfurt am Main, Germany, a new high-rise building is planned. This new building is located directly between the river Main and the eastern inner harbour. The high-rise building will have a height of about 75 m and will be founded on a Combined Pile-Raft Foundation (CPRF) in the tertiary, soft marl. The new structure will be constructed next to important, sensitive traffic infrastructure. The foundation of the new high-rise building adjoins directly existing historic quay structures, which are more than 100 years old. For analysis of the stability and the serviceability of the heavily eccentric loaded foundation of the new high-rise building and the existing structures and for the investigation of the soil-structure interaction complex three-dimensional, non-linear numerical simulations have been carried out. The paper introduces into a very complex construction project in which the realistic consideration of the soil-structure interaction is very important for the serviceability of the foundation of the planned high-rise building as well as for the surrounding infrastructure.

RÉSUMÉ: En raison de la croissance démographique dans les zones urbaines, même les immeubles de grande hauteur doivent être planifiés à proximité des infrastructures sensibles existantes. À l'est de Francfort-sur-le-Main, en Allemagne, un nouveau bâtiment de grande hauteur est prévu. Ce nouveau bâtiment est situé directement entre la rivière Main et l'arrière-port est. Le bâtiment de grande hauteur aura une hauteur d'environ 75 m et sera fondé sur une fondation combinée sur pieux et radeaux (CPRF) dans la marne tertiaire molle. La nouvelle structure sera construite à côté d'infrastructures de circulation importantes et sensibles. Les fondations du nouveau bâtiment de grande hauteur jouxtent directement les structures de quai historiques existantes, vieilles de plus de 100 ans. Pour l'analyse de la stabilité et de l'aptitude au service des fondations chargées fortement excentriquement du nouveau bâtiment de grande hauteur et des structures existantes et pour l'étude de l'interaction sol-structure, des simulations numériques complexe tridimensionnelles et non linéaires ont été réalisées. L'article introduit un projet de construction très complexe dans lequel la prise en compte réaliste de l'interaction sol-structure est très importante pour la fonctionnalité des fondations du bâtiment de grande hauteur prévu ainsi que pour l'infrastructure environnante.

Keywords: Numerical analysis, deep foundation, CPRF, high-rise building, soil-structure interaction

1 INTRODUCTION

A new high-rise building is planned in the east of Frankfurt am Main, Germany. The new building is located directly between the river Main and the eastern harbour. At the moment a filling covers the construction site, shown on Figure 1. The high-rise building will be a 75 m high hotel with 22 floors (Fig. 2). The hotel will be constructed directly by the roundabout intersection. Under the roundabout

intersection two levels will be constructed for building equipment and appliances, for the entrance and for parking. The vehicle access will be facilitated under the southern bridge along the river Main by a ramp.

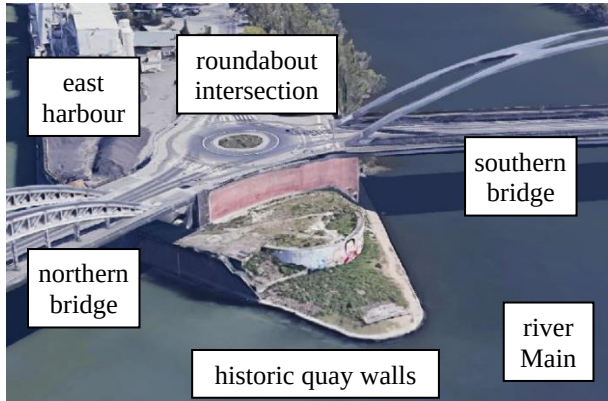


Figure 1. Construction site (google earth)

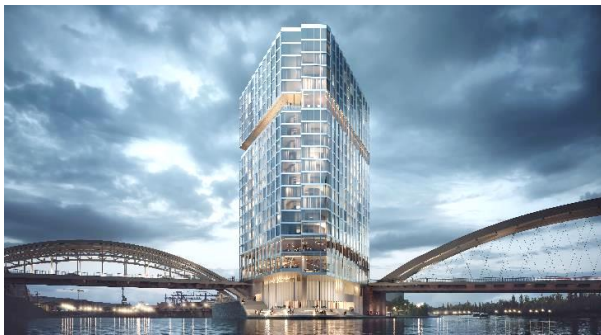


Figure 2. Visualisation of the planned high-rise building (B&L Group, Hamburg, Germany)

The high-rise building will be founded on a Combined Pile-Raft Foundation (CPRF). The 2 m thick foundation raft has a near to triangular shape and an area of 815 m². The load of the superstructure will be transferred into the CPRF through walls and columns also through a large single column at the tip of the triangular raft. The loads on the foundation raft are given in Table 1. The total load of the high-rise building including the foundation raft is estimated to be about $F_{\text{tot},k} = G_{\text{tot},k} + Q_{\text{tot},k} = 507 \text{ MN}$. The load has a non-symmetric distribution and is viewed as eccentric.

The foundation of the two levels under the roundabout intersection is a raft founded on micro piles. The micro piles are necessary to resist the uplifting at high water levels of the river Main. According to the regulations the whole project is classified into the Geotechnical Category GC 3, which is the category of the most complex construction projects (CEN 2004).

Table 1. Loads on the foundation raft

Structural element	Type of load (characteristic)	Load magnitude
Walls and columns	Dead load	325 MN
	Live load	60 MN
Highly loaded single column	Dead load	65 MN
	Live load	15 MN

On the construction site and in the direct neighbourhood the following structures exist:

- Roundabout intersection (centre of Fig. 1)
- Historic quay walls
- Southern abutment of the northern bridge (left in Fig. 1)
- Northern abutment of the southern bridge (right in Fig. 1)

The roundabout intersection is founded on a classic pile foundation. The space under the roundabout intersection is partly filled. This filling has to be removed for the construction of the two levels which will be used for the high-rise building also in order to place the micro piles. The structure of the roundabout intersection includes abutments of the northern and the southern bridge.

The construction site is surrounded by quay walls. The quay walls consist of unreinforced concrete walls and of sheet pile walls. The concrete walls are more than 100 years old.

The southern abutment of the northern bridge is a huge block of concrete. The northern abutment of the southern bridge was founded on classic pile foundation. Both abutments are integrated into the structure of the roundabout intersection.

2 SUBSOIL CONDITIONS

Mainly by two core drillings the subsoil was investigated with the following results:

- artificial filling (0.7 m to 16 m thick)
- quaternary alluvial clay
- quaternary sand and gravel
- tertiary marl (minimum 80 m thick)

In addition to the core drillings a comprehensive programme of in-situ tests and laboratory tests has been carried out to detect the soil mechanical parameters. Several environmental laboratory tests on soil samples were carried out to classify the effort for disposal this excavation material.

The groundwater level on the construction site is equal to that of the river Main. At high water levels the construction site would be partly submerged under water.

3 FOUNDATION OF HIGH-RISE BUILDING

The foundation of the high-rise building is planned as a CPRF. A CPRF is a hybrid deep foundation system

which combines the bearing capacity of a foundation raft and load transferring of the piles or barrettes. The CPRF is a technical and economical optimized foundation system. The CPRF can be used for the foundation of classic high-rise buildings as well as for engineering constructions like bridges and towers. For the CPRF, the same technical regulations as for classic deep foundations can be applied. To complete the design and safety concept the international Combined Pile-Raft Foundation Guideline has to be considered (ISSMGE 2013). Due to the interaction between the foundation elements and the subsoil CPRFs have a very complex bearing and deformation behaviour. Hence CPRFs have to be classified into the Geotechnical Category GC3 according to EC 7 (CEN 2004). The advantages of a CPRF compared to a conventional spread foundation and to a classic pile foundation are the reduction of:

- settlements and differential settlements
- the bending moments of the foundation raft
- pile materials (30 % to 50 %)

and the increasing of the bearing capacity of spread foundations. More explanations about CPRF and several examples from engineering practice are given in Katzenbach et al. (2016).

The comprehensive numerical analysis using the Finite-Element-Method (FEM) led to the optimized geometry of the CPRF with a thickness of 2 m for the raft and 34 piles with a diameter of 1.5 m and length of 40 m and 45 m. Figure 3 shows the FE-model of the CPRF.

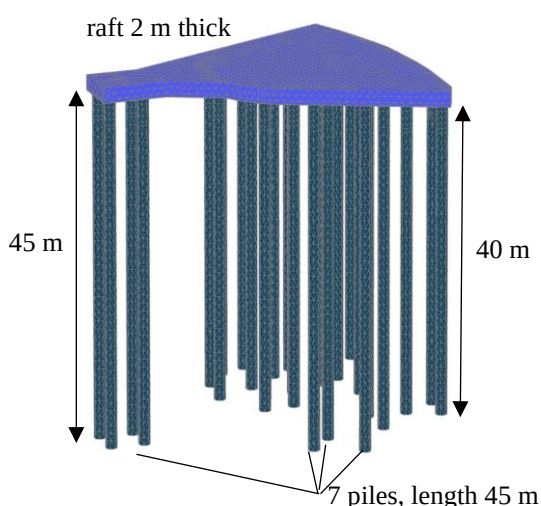


Figure 3. FE-model of the CPRF

4 NUMERICAL MODEL OF THE PROJECT

The 3-dimensional FE-model (cutout) of the project is shown in Figure 4. The complete model consists of about 772,000 tetrahedral 10-node elements with about 1,170,000 nodes. The modelled subsoil has a base area of 200 m x 200 m and a depth of 105 m. For executing the numerical analysis, the FE-software PLAXIS 3D was used. Figure 5 shows all single structures in the whole construction site.

All construction phases on the project area which have taken place over the years are simulated in a sequence of single steps:

- initial situation
- construction of the quay walls
- construction of the abutment of the northern bridge
- construction of the piles of the roundabout intersection
- construction of the superstructure of the roundabout intersection
- construction of the abutment of the southern bridge
- removal of the filling on the construction site and under the roundabout intersection
- construction of the bored piles of the CPRF and of the micro piles below the roundabout intersection
- construction of the foundation raft of the CPRF and of the roundabout intersection
- hardening of the foundation rafts
- activation of dead loads and traffic loads of the superstructures

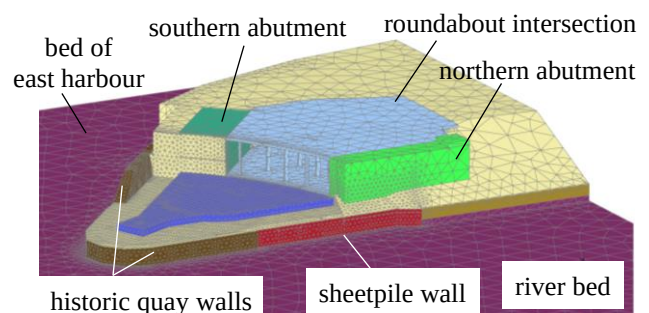


Figure 4. FE-model of the project (cutout)

These phases take into considerations the changes of stresses in the subsoil during all previous unloading and reloading of soil and stress cycles. It leads to a more realistic approach and estimation for the computed deformations as a result of constructing the new hotel building.

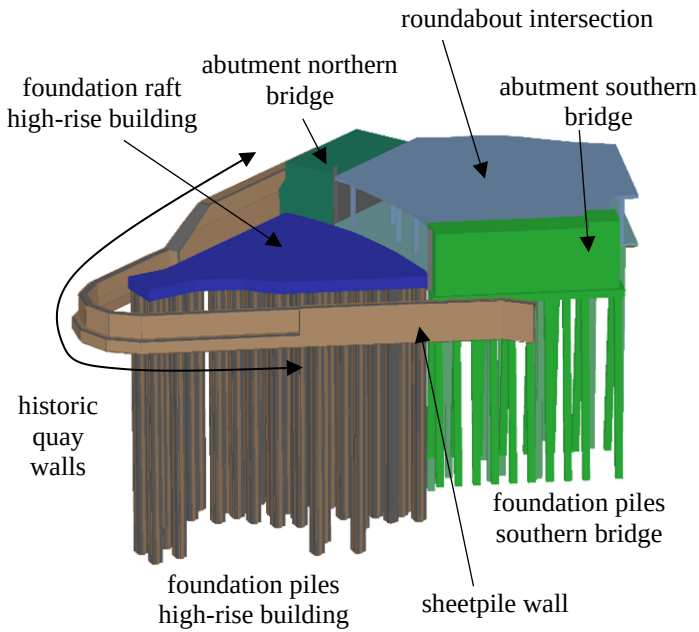


Figure 5. Structural model

Different constitutive material laws for the different material behaviour of the soil and the structures were implemented. For the material behaviour of the artificial fillings a linear elastic-ideal plastic constitutive material law was used including the failure criterion of Mohr-Coulomb (MC). For this constitutive material law the relation between the Young's modulus E and the stiffness E_s is defined by the Poisson ratio ν . In PLAXIS the modulus of stiffness E_s is named as E_{oed} according to the oedometer tests.

For the material behavior of the other soil layers the elasto-plastic constitutive material law "Hardening-Soil" (HS) was used. With this constitutive modelling the deformation behavior is described by a non-linear, hyperbolic, stress-dependent function, which enables the definition of different stiffness values depending on the stresses. Furthermore, effects of hardening after shear strain can be defined. The soil mechanical parameters used in the numerical simulation are shown in the Tables 2 and 3.

For the material behavior of the construction elements consisting of concrete respectively reinforced concrete (piles, rafts, walls etc.) and the sheet pile wall consisting of steel a linear elastic constitutive material law was used. In this constitutive material for the concrete resp. rein-forced concrete the Young's modulus is $E = 30.000 \text{ MN/m}^2$ and the Poisson ratio is $\nu = 0.2$. For the steel the Young's modulus is $E = 210.000 \text{ MN/m}^2$ and the Poisson ratio is $\nu = 0.3$.

Table 2. Soil mechanical parameters

Parameter	Symbol	Unit
Weight of saturated soil	γ_{sat}	kN/m^3
Weight of moist soil	γ_{unsat}	kN/m^3
Friction angle	ϕ'	$^\circ$
Cohesion	c'	kN/m^2
Dilatancy angle	Ψ	$^\circ$
Young's modulus / secant stiffness from triaxial test	$E / E_{50,ref}$	MN/m^2
Modulus of stiffness / tangent stiffness of first loading from oedometer test	$E_{oed,ref}$	MN/m^2
Tangent stiffness of unloading and reloading	$E_{ur,ref}$	MN/m^2
Poisson ratio / Poisson ratio for unloading and reloading	ν / ν_{ur}	--
Earth pressure coefficient at rest	K_0	--
Ratio of failure stress	R_f	--

Table 3. Values of soil mechanical parameters

	MC	HS		
	Filling	Quaternary alluvial clay	Quaternary sand and gravel	Tertiary marl
γ_{sat}	19	19	19.5	19
γ_{unsat}	19	19	19.5	19
ϕ'	20	25	35	22.5
c'	5	5	0	20
Ψ	0	0	5	0
$E / E_{50,ref}$	3	4	70	60
$E_{oed,ref}$	4	4	70	60
$E_{ur,ref}$		8	140	120
ν / ν_{ur}	0.3	0.3	0.3	0.25
K_0	0.5	0.5774	0.4264	0.6173
R_f	--	0.9	0.9	0.9

5 SPRING STIFFNESS AND SUBGRADE REACTION MODULUS OF THE HIGH-RISE BUILDING

For the structural analysis and dimensioning of the superstructure of the high-rise building the spring stiffness of the piles and the distribution of the subgrade reaction modulus of the raft are to be estimated and calculated. For the determination of the stiffnesses and the subgrade reaction modulus a FE-calculation was carried out with the sum of the full characteristic dead load $G_{tot,k}$ and the full characteristic traffic load $Q_{tot,k}$. The spring stiffness of the piles is defined by the relation of the load on the piles to the settlements of the pile head. The subgrade reaction modulus is defined by the relation

of the stresses under the raft to the settlements of the raft. The calculated settlements of the foundation are shown in Figure 6. The resulting spring stiffnesses and the subgrade reaction modulus for the calculation of the superstructure are shown in Figure 7.

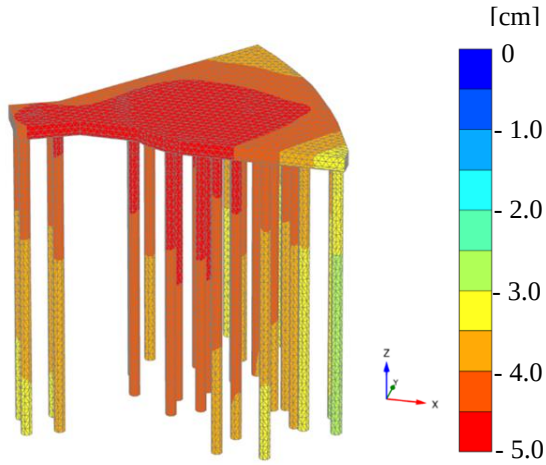


Figure 6. Calculated settlements of the CPRF for $(F_{tot,k} = G_{tot,k} + Q_{tot,k})$

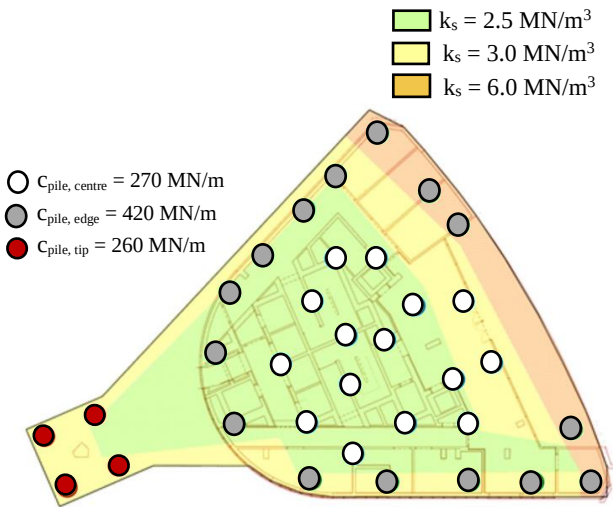


Figure 7. Spring stiffness and subgrade reaction modulus for calculation of the superstructure

6 BEARING BEHAVIOUR OF THE CPRF

The bearing behaviour of the CPRF can be specified by the CPRF coefficient α_{CPRF} . The coefficient declares the relation between the resistance of the piles ($R_{pile,k} = 450 \text{ MN}$) and the total resistance ($R_{tot,k} = F_{tot,k}$) of the whole CPRF (507 MN), as shown in Equation (1). The CPRF coefficient of $\alpha_{CPRF} = 0$ means that the whole load $F_{tot,k}$ is carried by the foundation raft. A CPRF coefficient of $\alpha_{CPRF} = 1.0$

means that the whole load $F_{tot,k}$ is carried by the foundation piles as a classic pile foundation.

$$\alpha_{CPRF} = \frac{\sum R_{pile,k,i}(s)}{R_{tot,k}(s)} = \frac{450 \text{ MN}}{507 \text{ MN}} = 0.89 \quad (1)$$

7 DISPLACEMENTS OF EXISTING STRUCTURES

For the investigation of the displacements of the existing structures as a result of the construction of the new high-rise building further FE-simulations were carried out. To estimate realistic displacements the simulations considered the full characteristic dead load $G_{tot,k}$ and 33 % of the characteristic traffic load $Q_{tot,k}$. As a so-called settlement active load F_{sett} the calculated settlements of the whole project area shown in Figure 8.

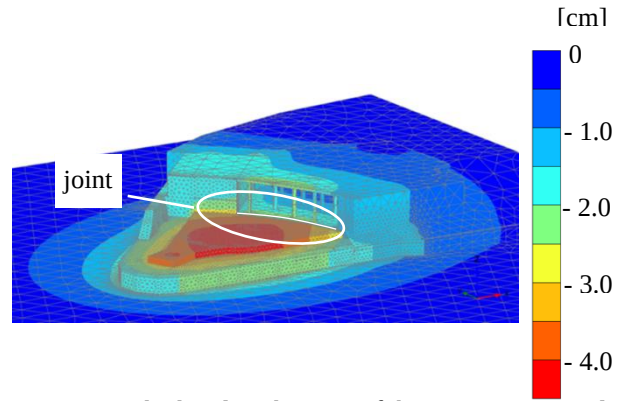


Figure 8. Calculated settlements of the project area and adjacent buildings for $[F_{sett} = G_{tot,k} + (1/3 \cdot Q_{tot,k})]$

The predicted settlements of the high-rise building are estimated to be 2.5 cm and 4.5 cm. The predicted settlements of the existing bridge abutments and the structure of the roundabout intersection are between 0 cm and 2.5 cm, which in this case will not lead to any damage to these structures. The construction detail of the joint between the new high-rise building and the sublevels in the roundabout intersection (see Fig. 8) is very important for the serviceability of the new structure. The calculation forecasts differential settlements of about 0.5 cm and 2.0 cm. For these differential settlements the joint has to be designed to guarantee a watertight and plane passage.

The existing historic quay walls are very sensitive structures. The FE-simulation shows that the horizontal displacements in x-direction (Fig. 9 top) and in y-direction (Fig. 9 bottom) will be between 0 cm and ± 0.5 cm. This will not lead to any major or considerable damage for these structures.

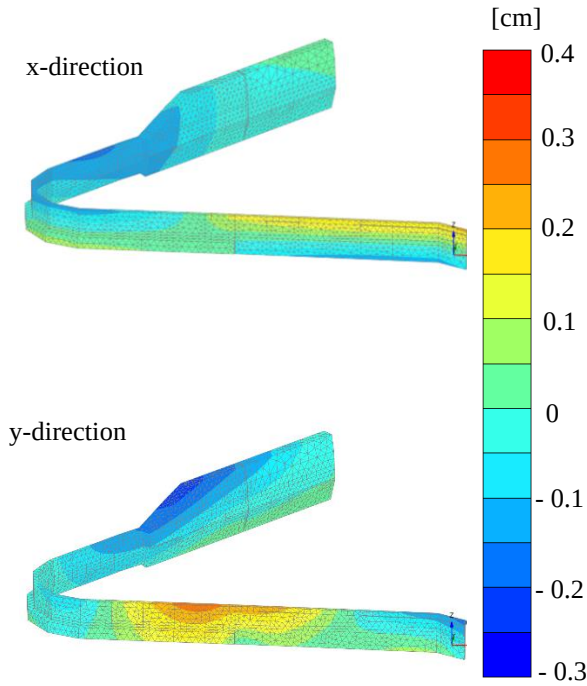


Figure 9. Calculated horizontal displacements of the quay walls for $[F_{sett} = G_{tot,k} + (1/3 \cdot Q_{tot,k})]$

Regarding the settlements of the historic quay walls the prediction is between 1 cm and 3 cm as shown in Figure 10. For the evaluation of the stability and the serviceability the criterion of maximum angular rotation ψ will be applied. For the prevention of any fissures in any structure the criterion is $\psi \leq 1/500$ (GGS 1993). The predicted maximum angular rotation of the historic quay walls is $\psi = 1/1,000$. Hence there will be no danger of damage for the historic walls.

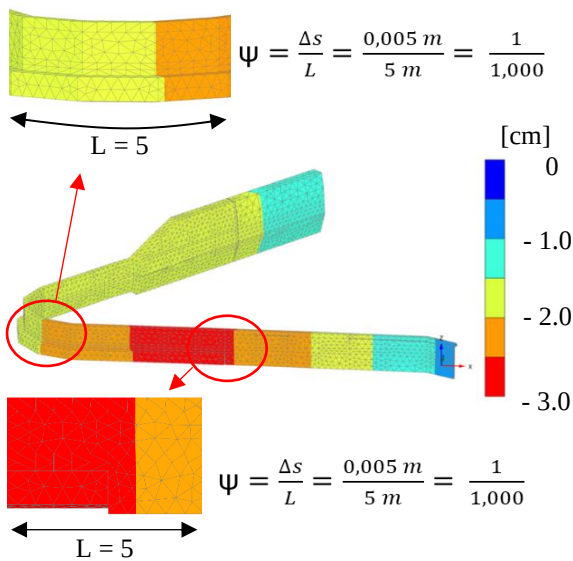


Figure 10. Calculated settlements of quay walls for $[F_{sett} = G_{tot,k} + (1/3 \cdot Q_{tot,k})]$

8 CONCLUSIONS

For analysis of the stability and the serviceability of the heavily eccentric loaded foundation of the new high-rise building and the existing structures and for the investigation of the soil-structure interaction complex three-dimensional, non-linear numerical simulations are very important. These numerical simulations have to take into account all geometric and material specific boundary conditions, including the history of the construction of the whole area.

The numerical simulations delivered the spring stiffness and the subgrade reaction modulus, which are needed for the analysis and the design of the superstructure.

The hybrid foundation system CPRF transfers the building load into the subsoil by the piles and by the raft. This leads to an optimized construction with a minimized impact on the environment.

Regarding the horizontal and vertical displacements of the existing structures due to the new high-rise building the numerical simulations show, that there will be no considerable risk.

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