Furthermore, the constructions in this area cause high loads on the foundation slabs. Since the expected subsoil conditions in the concerned area have to be classified as soft to very soft in most of the soil layers, a deep soil improvement by rigid inclusions was planned and investigated by different analyses. In order to estimate the prospective settlements of the different components of the construction, settlement analyses with analytical methods were performed in advance and more complex finite-element analyses (3DFoundation) were carried out in order to obtain more detailed information.

The performed analyses were initiated by similar conditions for a real project, but it is clearly stated, that the presented analyses do not represent direct input from the real project and results cannot be compared to monitoring data. The aim of the numerical analyses is to show how the estimation of the final settlements and of the required consolidation time can be performed.

Underground conditions and modelling
Based on the results from underground investigations in the vicinity of the investigated area by cone penetration tests and core drillings an underground model consisting of five layers was developed for the 3D finite element analysis. Generally, the subsoil conditions in the first 35 metres below the top ground surface (approximately flat) are described as an alternating layering of sandy, silty clay and gravel with different thickness:

0 m to 6 m, 8 m to 18 m below surface and below 21 m: sandy, silty, clay
consistency: soft to very soft
\( E_{\text{oed}}^\text{ref} = 4,000 \text{ kN/m}^2 \), \( E_{\text{ur}}^\text{ref} = 12,000 \text{ kN/m}^2 \),
\( p^\text{ref} = 100 \text{ kN/m}^2 \), \( m=0.85 \)
OCR=1.0, POP = 0

6 m to 8 m and 18 m to 21 m below surface:
gravel
consistency: loose
\( E_{\text{ur}}^\text{ref} = 32,000 \text{ kN/m}^2 \), \( E_{\text{ur}}^\text{ref} = 96,000 \text{ kN/m}^2 \),
\( p^\text{ref} = 100 \text{ kN/m}^2 \), \( m=0.5 \)
OCR=1.0, POP = 0

Due to the fact that deep soil improvement by rigid inclusions is common practice when soft underground conditions are explored, a study including analytical and numerical analyses was performed. For the full study, a large field with different commercial constructions was investigated, whereas a local part with which was classified as very sensitive relating to settlements and/or differential settlements was analyzed in detail.

Figure 1: Bottom view of deep gravel layer below 18 m, visualisation of the varying layer thickness (calculation model without lowest clay layer)
For the second gravel layer in between of 18 and 21 metres below surface a very local changing of the thickness was adopted in order to model a local weakness directly below the foundation slab. The shape of the area with reduced thickness of the gravel layer was estimated by almost concentrical rectangles, whereas the thickness of the layer reduces from 3 metres to 2, 1 and 0.5 meter(s) (Figure 1). In reality, the shape would show a more continuous decrease of thickness. For the sake of a simple finite-element-mesh this type of modelling was chosen to allow for more complexity in the area of the rigid inclusions. A smooth shape was modelled in the beginning (first trials) by using 18 “instant” boreholes, but the entire mesh with the rigid inclusions (volume elements) resulted in a six-digit number of finite-elements and was therefore not followed. The chosen model for calculation has dimensions of 60 by 60 metres in plan view and reaches to a maximum depth of 35 metres. The groundwater table was explored in a depth of approximately 1 metre below the to ground surface. For the 3D finite-element-analyses the Hardening Soil Model was used for modelling the deformation behavior of the soil layers.

The foundation slab, which has an irregular shape in plan view and the nearly 100 rigid inclusions directly below the slab were modelled as volumetric elements assuming linear elastic behavior. The rigid inclusions were modelled according to an almost regular layout from the bottom of the slab to the top surface of the deep gravel layer. The used finite-element-model consists of 63,750 15-noded elements (prisms and tetrahedrons) and involves approximately 170,000 nodes. Figure 2 gives an impression of the finite-element model incorporating the high number of rigid inclusions.

Loading situation

Based on a possible configuration of the construction the following loading situation was developed for the numerical analysis. Due to the fact that a large number of single loads with minor influence on the overall settlement behavior of the slab would be present in the adopted construction, a simplified pattern with respect to the major loads was incorporated. Therefore, the top surface of the foundation slab was divided into 5 zones for modelling uniform distributed loads in each of them.

The value for each zone represents the mean value of the corresponding loads. The centre zone contains the main part with a high-rise construction. In zone II additional point loads were considered, whereas lower loads are present in zones III, IV and V. Figure 3 shows a sketch of the modelled load pattern in plan view.
Figure 3: Sketch of the different loading zones

Figure 4: Contour plot of settlements, partial geometry

Figure 5: Deformation of deep sand layer, bottom view, partial geometry
Plaxis Practice: 3D finite element analyses of deep soil improvement

Modelling of the discontinuity of deep gravel layer:
Reduction of thickness by changing the corresponding material data sets.

Installation of rigid inclusions:
Effects due to the installation process have not been taken into account; the activation of the rigid inclusions happened by changing the material parameters (wished-in-place).

Installation of foundation slab:
Activation of the concrete slab with a thickness of 0.9 metres.

Loading situation:
The load distribution presented before was activated in two calculation phases (50% and 100%).

As already mentioned, the main focus in this drained analysis was the determination of the prospective settlements in the final state (after decisive consolidation phase). Due to the calculation results, the maximum settlement in the centre of the foundation slab is approximately 33 mm, whereas the settlements along the boundary of the slab are in the range of 24 to 30 mm. Differential settlements in the centre part are in the range of 2 to 3 mm.

Figure 4 shows a contour plot of the settlements in the area of the foundation slab and the rigid inclusions. Looking at the columns closely, it can be seen that the compression of the rigid inclusions is very small and that local dents in the deep sandy layer are visible (Fig. 5).

However, failure by punching of the columns in the partly very thin gravel layer below the toes of the rigid inclusions is not indicated by the analysis (plastic points plot, stress distributions – not shown here).

Regarding the consolidation time, the simplified model (no detailed discretisation of columns) resulted in approximately 90 days (3 months) to reach 95% of the final settlements. Approximately 50% of the estimated settlements were predicted after approximately 30 days (1 month).

In order to define the estimated development of settlements with time and to form a basis for comparison with monitoring data, the following diagram was derived from the calculation results. Figure 6 shows the results of the drained and undrained analysis and gives a band width for the estimated settlements in the centre of the slab and points along the boundary, respectively.

Conclusions
The presented boundary value problem could be solved by using the finite-element-method incorporating 3DFoundation. Despite of the problems with too large systems (too many elements) for undrained analysis, the presented boundary value problem could be solved and an estimation of final settlements and consolidation time could be derived. With the presented diagram in Figure 6, the basics for comparison of calculation results and monitoring data were prepared.

For the finite-element-analysis, the following uniform pressures have been considered:
- Zone I: ca. 138 kN/m²
- Zone II: ca. 37 kN/m²
- Zone III: ca. 24 kN/m²
- Zone IV: ca. 21 kN/m²
- Zone V: ca. 22.5 kN/m²

Due to the fact that the concrete slab was modelled by using volumetric elements, the weight of the concrete slab with a thickness of 0.9 meters is not included in the given values. The additional weight due to the installation of the rigid inclusions was modelled by increasing the unit weight of the corresponding material data set.

Calculation procedure and results
As already mentioned, the aim of the calculations was an estimation of settlements and consolidation time. In order to fulfill both requirements in one analysis, undrained conditions and corresponding consolidation steps were defined.

Due to the size of the model, calculation time and stability were problematic and therefore, a different way of solving the problem was chosen. This means, that finally an analysis with drained conditions was performed with the presented model for an estimation of the settlements and another model using a less accurate discretisation of the rigid inclusions – blocks with mean material parameter sets – and undrained subsoil conditions was used for estimating the consolidation time.

For the analysis with the presented model, the following calculation steps have been defined: Initial state (K₀-procedure):

\[ K_0 = 1 - \sin \phi \] deep sand layer with constant thickness of 3 metres

For the analysis with the presented model, the following calculation steps have been defined: Initial state (K₀-procedure):

\[ K_0 = 1 - \sin \phi \] deep sand layer with constant thickness of 3 metres

However, failure by punching of the columns in the partly very thin gravel layer below the toes of the rigid inclusions is not indicated by the analysis (plastic points plot, stress distributions – not shown here).

Regarding the consolidation time, the simplified model (no detailed discretisation of columns) resulted in approximately 90 days (3 months) to reach 95% of the final settlements. Approximately 50% of the estimated settlements were predicted after approximately 30 days (1 month).

In order to define the estimated development of settlements with time and to form a basis for comparison with monitoring data, the following diagram was derived from the calculation results. Figure 6 shows the results of the drained and undrained analysis and gives a band width for the estimated settlements in the centre of the slab and points along the boundary, respectively.

Conclusions
The presented boundary value problem could be solved by using the finite-element-method incorporating 3DFoundation. Despite of the problems with too large systems (too many elements) for undrained analysis, the presented boundary value problem could be solved and an estimation of final settlements and consolidation time could be derived. With the presented diagram in Figure 6, the basics for comparison of calculation results and monitoring data were prepared.

For the finite-element-analysis, the following uniform pressures have been considered:
- Zone I: ca. 138 kN/m²
- Zone II: ca. 37 kN/m²
- Zone III: ca. 24 kN/m²
- Zone IV: ca. 21 kN/m²
- Zone V: ca. 22.5 kN/m²

Due to the fact that the concrete slab was modelled by using volumetric elements, the weight of the concrete slab with a thickness of 0.9 meters is not included in the given values. The additional weight due to the installation of the rigid inclusions was modelled by increasing the unit weight of the corresponding material data set.

Calculation procedure and results
As already mentioned, the aim of the calculations was an estimation of settlements and consolidation time. In order to fulfill both requirements in one analysis, undrained conditions and corresponding consolidation steps were defined.

Due to the size of the model, calculation time and stability were problematic and therefore, a different way of solving the problem was chosen. This means, that finally an analysis with drained conditions was performed with the presented model for an estimation of the settlements and another model using a less accurate discretisation of the rigid inclusions – blocks with mean material parameter sets – and undrained subsoil conditions was used for estimating the consolidation time.

For the analysis with the presented model, the following calculation steps have been defined: Initial state (K₀-procedure):

\[ K_0 = 1 - \sin \phi \] deep sand layer with constant thickness of 3 metres

However, failure by punching of the columns in the partly very thin gravel layer below the toes of the rigid inclusions is not indicated by the analysis (plastic points plot, stress distributions – not shown here).

Regarding the consolidation time, the simplified model (no detailed discretisation of columns) resulted in approximately 90 days (3 months) to reach 95% of the final settlements. Approximately 50% of the estimated settlements were predicted after approximately 30 days (1 month).

In order to define the estimated development of settlements with time and to form a basis for comparison with monitoring data, the following diagram was derived from the calculation results. Figure 6 shows the results of the drained and undrained analysis and gives a band width for the estimated settlements in the centre of the slab and points along the boundary, respectively.

Conclusions
The presented boundary value problem could be solved by using the finite-element-method incorporating 3DFoundation. Despite of the problems with too large systems (too many elements) for undrained analysis, the presented boundary value problem could be solved and an estimation of final settlements and consolidation time could be derived. With the presented diagram in Figure 6, the basics for comparison of calculation results and monitoring data were prepared.

For the finite-element-analysis, the following uniform pressures have been considered:
- Zone I: ca. 138 kN/m²
- Zone II: ca. 37 kN/m²
- Zone III: ca. 24 kN/m²
- Zone IV: ca. 21 kN/m²
- Zone V: ca. 22.5 kN/m²

Due to the fact that the concrete slab was modelled by using volumetric elements, the weight of the concrete slab with a thickness of 0.9 meters is not included in the given values. The additional weight due to the installation of the rigid inclusions was modelled by increasing the unit weight of the corresponding material data set.

Calculation procedure and results
As already mentioned, the aim of the calculations was an estimation of settlements and consolidation time. In order to fulfill both requirements in one analysis, undrained conditions and corresponding consolidation steps were defined.

Due to the size of the model, calculation time and stability were problematic and therefore, a different way of solving the problem was chosen. This means, that finally an analysis with drained conditions was performed with the presented model for an estimation of the settlements and another model using a less accurate discretisation of the rigid inclusions – blocks with mean material parameter sets – and undrained subsoil conditions was used for estimating the consolidation time.

For the analysis with the presented model, the following calculation steps have been defined: Initial state (K₀-procedure):

\[ K_0 = 1 - \sin \phi \] deep sand layer with constant thickness of 3 metres

However, failure by punching of the columns in the partly very thin gravel layer below the toes of the rigid inclusions is not indicated by the analysis (plastic points plot, stress distributions – not shown here).

Regarding the consolidation time, the simplified model (no detailed discretisation of columns) resulted in approximately 90 days (3 months) to reach 95% of the final settlements. Approximately 50% of the estimated settlements were predicted after approximately 30 days (1 month).

In order to define the estimated development of settlements with time and to form a basis for comparison with monitoring data, the following diagram was derived from the calculation results. Figure 6 shows the results of the drained and undrained analysis and gives a band width for the estimated settlements in the centre of the slab and points along the boundary, respectively.

Conclusions
The presented boundary value problem could be solved by using the finite-element-method incorporating 3DFoundation. Despite of the problems with too large systems (too many elements) for undrained analysis, the presented boundary value problem could be solved and an estimation of final settlements and consolidation time could be derived. With the presented diagram in Figure 6, the basics for comparison of calculation results and monitoring data were prepared.