



PLAXIS 3D analysis of the Groninger Forum

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The Groninger Forum will be constructed in the center of Groningen city, the Netherlands. The building is commissioned by the Groningen municipality. This 45-m-height and eccentric-styled cultural center will include a library, museums, cinemas, restaurants and bars. Two basements complete the structure: a five-storey car park (suitable for 390 cars) and a one-storey bicycle parking (suitable for 1,500 bicycles). The car park is located exactly underneath the main structure, whereas the bicycle parking keeps a horizontal distance from it. Figure 1 shows a cross-section of the building and the two basements.

➤ The deep excavation required to realize the car park, is designed by ABT (Adviseurs in Bouwtechniek). Diaphragm walls will be the retaining system for the excavation and will be supported horizontally by two layers of steel struts (one at 1.5m and the other at 4.5m depth) and an underwater concrete slab. Tubex Grout Injection Piles (screwed piles with lost tube, lost pile tip and a grout injection) and Gewi anchors avoid uplift failure of the concrete slab. The excavation pit is completely surrounded by adjoining properties, which are within short distances of at least 2.5 m up to 12.5 m. These adjacencies are mainly established on shallow foundation; a single extension is founded on piles.

Besides the complexity in the stratigraphy (see Table 1), there is also a geometrical asymmetry in the plan view of the excavation. On the west side, it comprises a semi-circle with a diameter of about 36 m. The east side is roughly a rectangle with 43 m in width and 105 m in length. This sums a total perimeter of 267 m. The bottom of the excavation is located 18 m below the surface.

Project challenges

There are several reasons to use a three-dimensional finite element program to design the deep excavation:

- On the west side the surface level is approximately 2.5 to 3.0 m higher than on the east side
- There is a significant difference in soil stratigraphy between the two sides of the excavation (see Table 1)

The west side comprises only Loam and sand layers. The east side contains in addition a 12-meter-thick heavily overconsolidated clay layer (OCR = 2 to 3), known in the Netherlands as Potklei

- The phreatic groundwater level on the west side is 2 m higher than on the east side
- Monumental buildings are present very close to the excavation. The most vulnerable dates from the year 1130 AC and is situated at the corner of the excavation
- At the final design, the diaphragm wall on the west side is circular shaped, while on the east side it is rectangular

The first design was made in 2008, with PLAXIS 3D Foundation. With this program it was only possible to work with horizontal workplanes.

The inclining surrounding terrain was therefore schematized by several small vertical steps, see Figure 2. With this 3D model it became clear that the deformations around the building pit are not equal everywhere. Especially at the corners of the excavation pit, the deformations are much smaller.

A second, high positioned, temporary strut was added, to decrease the deformations furthermore. Also the water level inside the building pit was increased during excavation under water. With these measures the risk for damages became acceptably low.

With the release of the program "PLAXIS 3D" a more detailed schematization of the different building stages and the addition and removal of strut tubes became possible.

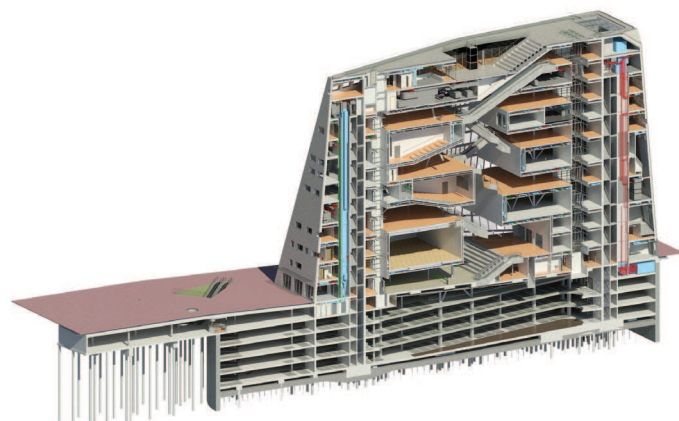


Figure 1: Cross section of "Groninger Forum"



Stage construction possibilities

The initial idea of the construction sequence considered that the upper struts are installed before installing the lower ones. The procedure was to remove the upper strut and then place it back a few meters lower at the lower frame. This had to be repeated for each of the struts, having at the end all the lower struts in place and all the upper struts removed. This method was partly inspired by the traditional way of calculating with two-dimensional programs.

The second idea was to install only 3 or 4 (at a total of 15) of the upper struts and then advance with the first of the lower struts. However, this approach had a practical constraint: a mobile crane can only lift the 40-ton strut at close range.

To overcome this limitation, the following procedure is developed. Only the minimum excavation necessary to install a single strut is made. After the installation, the mentioned excavation is backfilled and only then the complete procedure is repeated for the next strut. This stage construction procedure is hereafter called the ESBM (which stands for local Excavation – Strut installation – Backfilling Method).

It should be noted that this approach results in a considerable amount of earthworks, but also in a significant reduction of the excavated volume at a given time. The latter remark means that the soil deformations during the installation of the struts are reduced. Hence, there is the possibility that two layers of struts are not necessary anymore. At least in theory.

ESBM with a single layer of struts

A feasibility study was started considering only the use of the deep struts (i.e. the lower struts). To this end, a PLAXIS 3D model was made, in which all sub-phases for the laying of the several tubes have been schematized step by step.

A number of oblique surfaces were added to the 3D mesh, making it possible to input the

Layers	West-side	East-side
Surfacelevel	NAP + 7,3 m	NAP +4,3 m
Toplayer (sand, clay, debris)	from +7,3 m to +3,0 m	from +4,3 m to +0,0 m
Loam	from +3,0 m to -6,0 m	from +0,0 m to -6,0 m
"Potklei"	-	from -6,0 m to -18,0 m
Sand, stiff	from -6,0 m to -40 m	from -18,0 m to -40 m
Max depth site investigation	-40 m	

Table 1: Soil stratigraphy

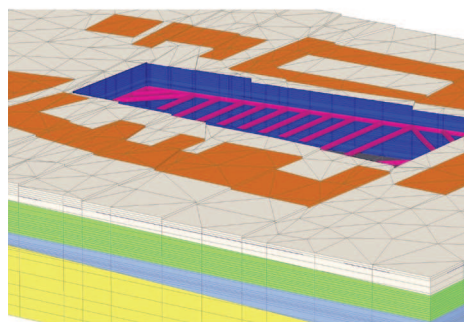


Figure 2: PLAXIS 3D foundation model with small vertical steps

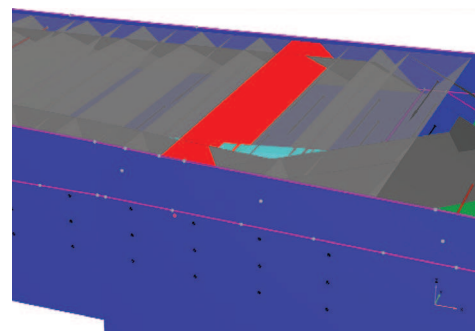


Figure 3: Extra surfaces in the 3D mesh

forementioned local excavations inside the main excavation area. Figure 3 shows the volumes representing the local excavations.

The excavation-installation-backfill procedure is performed for each strut from East to West until all of them are in place. The remaining soil in the western part of the main excavation prevents deformations of nearby adjacent structures.

Once the deep struts are laid, more deformation at the East is prevented. Hence, deformations only occur in the vicinity of where the slots are excavated at that time. The deformation of the adjacent structures walk along with the excavation of trenches and laying of the struts (Figure 4). From this feasibility study it can be concluded that the deformations under the nearby adjacent buildings (if the ESBM with a

single layer of struts is performed) are significantly lower than when excavating the whole area until the lower struts level at once. Nevertheless, since the deformation levels were in the order of the allowed deformations, it was finally decided not to discard the use of the temporary upper struts.

Photo 1 shows the required soil excavation for the placing of the different tubes in the upper and lower layer of struts. Figure 5 shows the detailed modelling in PLAXIS 3D in the final calculation. Figure 6 shows the complete model, which can be compared with the aerial picture of the real situation in Photo 2.

Modelling challenges

The diaphragm walls are not modelled with volume elements but with plate elements. For the struts, beam elements and node-to-node anchors are used. The surrounding soil is modelled as a Hardening Soil (HS) material and to be fully drained (the latter choice is justified since the goal is to compute deformations). Table 2 presents the main soil parameters. The underwater concrete slab is modelled by volume elements with a surface load on top to compensate the upward water pressures (in reality this compensation will be provided by the piles and anchors that are excluded in the simulation).

		Loam	"Potklei"	Sand
γ/γ_{sat}	[kN/m ³]	19/21	14,5/18,5	19/21
$E_{50}/E_{oed}/E_{ur}$	[MN/m ²]	9/4,5/36	12/6,4/48	110/110/440
c	[kN/m ²]	2,5	20,0	0
φ	[°]	27,5	17,5	32,5

Table 2: Main soil parameters

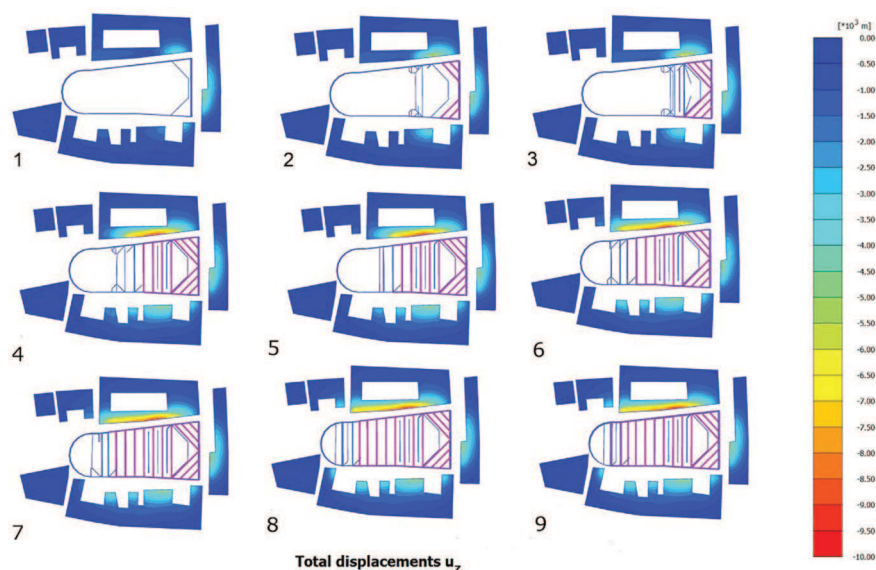


Figure 4: Vertical deformation of the adjacent structures "walk along"

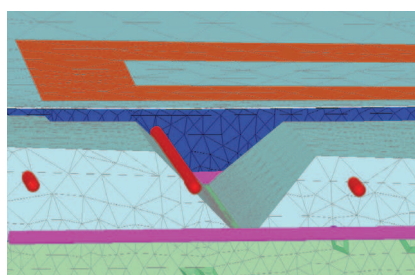


Figure 5: Detailed modelling PLAXIS 3D



Photo 1: Required local excavation to install a lower strut

All the extra oblique surfaces resulted in a mesh with an important number of elements: more than 500.000. The calculation of the intersections between the soil stratigraphy and the structures (performed by PLAXIS 3D when switching to the tab Mesh) took significant time. But after that, the meshing itself was performed successfully and in a shorter time frame.

Different stages had to be calculated using different solvers. The Classic solver used less memory, but it took more time to calculate. The Pardiso solver worked faster, but could give a singular matrix in case of some structural elements. It's still not clear why. But fortunately, the Picos solver was able to deal with the situation in which structural elements were switched on and soil element were switched off due to the excavation. So, by switching between the different solvers, the whole calculation could be finished efficiently.

The calculation of the stages required more than 14 GB RAM-memory and around 30 GB of disk space. To prevent a lack of space available for the Windows temporary folder (TEMP), the project was saved after each phase was calculated. This was done using the commands runner.

Monitoring

The impact of the excavation on the surroundings is closely monitored, using inclinometers in the diaphragm walls and a large number of measuring bolts in the facades of the adjacent buildings. The estimated horizontal deflection of the diaphragm walls using the PLAXIS 3D model was about 20 to 30 mm. The measured horizontal deformations were smaller: just a few millimetres with a maximum of 7 mm.

The lower deformations occurred in reality can be attributed to:

- the higher stiffness of the Potklei. The overconsolidation ratio of the clay was not taken into account in the model, which in other words means an underestimation of the initial horizontal stresses and thus in the actual elastic moduli of the HS model
- the higher stiffness of the diaphragm wall. In reality, the diaphragm wall showed practically uncracked behaviour, but in the model an elastic modulus corresponding to a cracked wall was considered

Moreover, the final measured subsidence of the adjacent structures are lower than the estimated in the model. They are compared in the following paragraph for: a) the buildings at the North and East side of the excavation at a perpendicular distance of 5 m from the excavation and b) buildings at the corners of the excavation, including the monument.

As a result of the installation of the various diaphragm wall panels, the measured vertical deformations at the North and East side of the excavation were 1 to 2 mm. The actual excavation and dewatering caused additional vertical deformations of a few millimetres up to 7 mm.

The estimated deformations at the North and East side of the excavation were 10 to 15 mm. The monument experienced a settlement of 5 mm, whereas in the model a settlement of 6 mm was estimated.

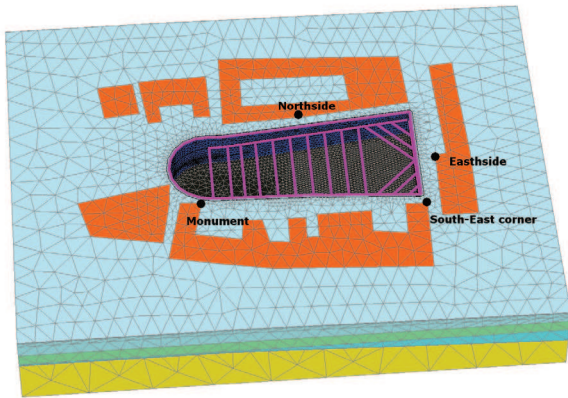


Figure 6: PLAXIS 3D mesh



Photo 2: Photography Koos Boertjens © ABT

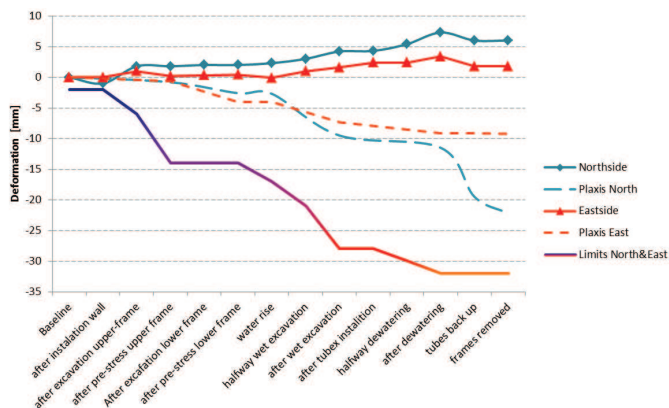


Figure 7

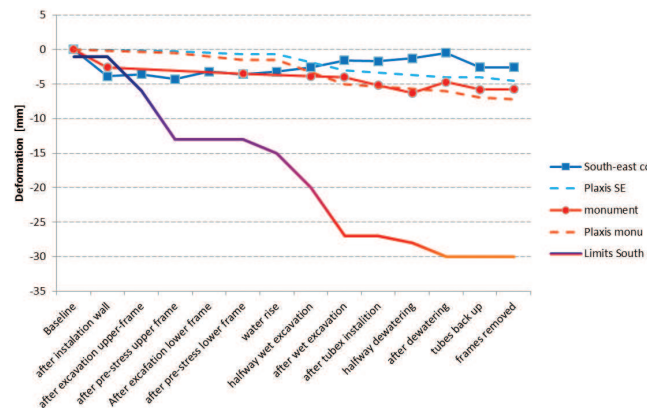


Figure 8

Figures 7 and 8 show graphs of the measured and calculated settlements as well as the allowed deformation at 4 relevant points. The location of these points are indicated in Figure 6. These figures show that the calculated settlements are less than the allowed, thus the risk of damage of the buildings was acceptably low. The actual measured settlements are lower and some points even showed upward rather than downward movement.

This phenomenon could be explained by the fact that, in the model, the upward pore pressures acting at the bottom of the underwater concrete slab were balanced by a non-existent external surface load. Hence, there is an increase in compressive stresses around the bottom of the excavation with a correspondent increase of downward movement. In reality, the Gewi and Tubex piles transfer the force generated by the upward pore pressures to deeper ground layers without increasing the compressive stresses at the bottom of the excavation. Since the excavation produces a reduction in compressive stresses at

the bottom of the excavation, the soil around this location will experience an upward movement. Clearly, this leaves the possibility of a net upward movement at the surface, as long as the sum of the settlements experienced by the shallow layers is lower than the sum of upward movements experienced by the deep layers.

By adding vertical embedded or volume piles in a PLAXIS model underneath the underwater concrete, the increase of compressive stresses produced by the external load could be avoided. This could result in a more realistic deformation of the surrounding. Alternatively, the external load can be combined with a decreased γ_{sat} of the underlying ground layers, in order to reduce the negative effect of the external load.

Conclusions

With the use of a comprehensive PLAXIS 3D model, including temporary structural elements and a detailed phasing, it is possible to optimize the implementation of a large and complex deep excavation successfully. To calculate more

accurate vertical deformations of the surrounding soil mass in case of a deep excavation with underwater concrete, it is important to model the unloading due to the excavation. This could be done by including the tension piles in the model.