Prediction of soil deformations during excavation works for the renovation of "Het *Nieuwe* Rijksmuseum" in Amsterdam, The Netherlands

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Introduction

The "Rijksmuseum" in Amsterdam is one of the most important 19th century monumental buildings in The Netherlands. The showpiece of the museum is the world famous The Night Watch by Rembrandt. Presently the building is being renovated in order to meet the modern standards for international museums. The design of the renovation has been drawn by Cruz y Ortiz from Sevilla. The constructive design is being carried out by ARCADIS in cooperation with CRUX Engineering and WARECO for the assessment of the geotechnical and hydrological implications of the project. The most striking feature in the new design is a semi-underground square of approximately 3000 m² in between the existing monumental building. This square is situated in the existing court yards and will serve as main entrance to the museum. The geotechnical design calculations are carried out by CRUX using the Finite Element program PLAXIS. The calculations are part of the risk assessment strategy in order to predict and judge the influence of ground deformations due to the excavations on the surrounding building. Intensive monitoring is used to control the deformations of the structure and the sheet pile walls during the construction work.

General

The realization of the lowered square and underground facility rooms requires the construction of concrete cellars with a depth of 6 m or more, right next to the existing wooden foundation piles of the monumental building. The cellars will be cast in building pits, the excavation of which will cause relaxation of the soil, inducing deformations in the near vicinity of the pits. These deformations, caused by the excavation works, have been predicted using PLAXIS. Figure 1 shows an artist impression of the court yards with lowered ground level. Figure 2 shows the museum in cross section. Below the court yards cellars will be realised for use as conference rooms, an auditorium and the kitchen.

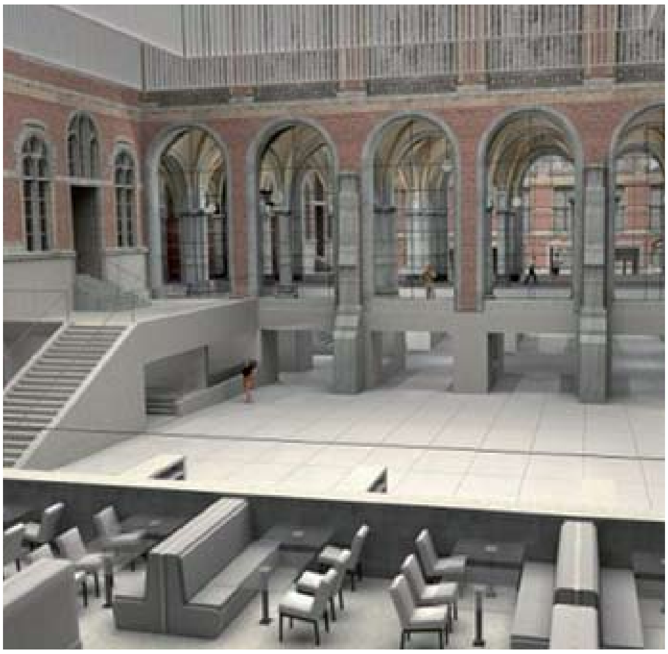

Figure 1. Artist impression of the lowered court yards (source JNDG-Amsterdam)

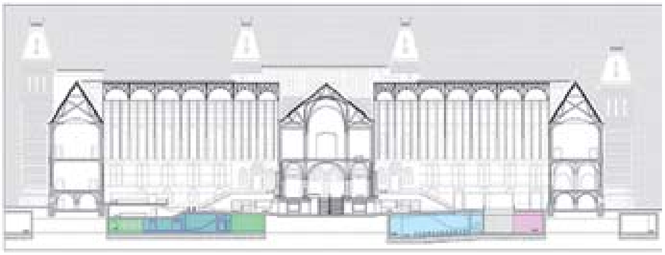

Figure 2. Cross section

Soil Conditions

For the project 18 electric cone penetration tests (CPT) have been performed. The CPTs show the soil profile that is typical for Amsterdam. The top layer of 2 m to 3 m below surface level consists of Anthropogenic sand. Below this toplayer the Holocene deposits are found to a depth of about 13 m below surface level. The Holocene formation can be divided (from top to bottom) into 1 m to 2 m peat (Hollandveen), 1 m to 2 m clay (Oude Zeeklei), 3 m silty sand (Wadzand), 3 m clay (Hydrobiaklei) and 0,4 m peat (Basisveen). The soft Holocene has been deposited on top of the stiff Pleistocene sands consisting of the so called first sand layer of 2 to 3 m thickness, an intermediate silty, clayey sand layer (Allerod) of 2 m and the second sand layer of at least 5 m thickness. The phreatic water level is about 0,4 m below surface level. The artesian water level in the first sand layer lies 2 m below the phreatic water level.

PLAXIS Model

A schematic soil profile that best fits the CPTs has been constructed for the model geometry. For modelling the soil layers the Hardening Soil model has been adopted. This model is most suitable for excavations. It is capable of describing reduction of stiffness as well as irreversible deviator strains due to deviatoric stress. In the vicinity of the excavation (on the active side) deviatoric stress applies. The horizontal stresses are reduced more compared to the vertical stresses. This results in friction hardening which is a feature of the Hardening Soil model. Friction hardening also occurs at the passive side of the sheet pile (that is, below the bottom of the pit). Here horizontal stress increases compared to the vertical stress due to (horizontal) movement of the sheet pile on the one hand and reduction of vertical stress as a result of the excavation on the other hand.

In order to get parameters for the Hardening Soil material set, almost 50 samples have been taken from 13 borings. Four soil layers have been tested: Hollandveen, Oude Zeeklei, Wadzand and Hydrobiaklei. These layers are considered to be most important regarding deformations due to the excavation. Besides testing the volumetric weight (γ), triaxial tests and oedometer tests have been performed for determining stiffness parameters (E_{50}, E_{oed}) and strength parameters (c', φ'). The parameters from the laboratory tests

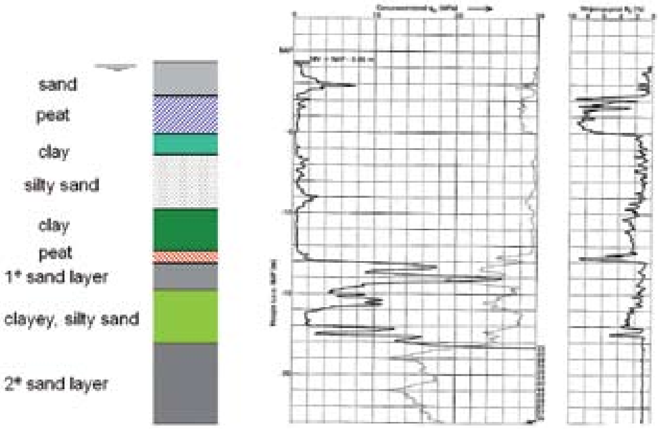

Figure 3. Characteristic Soil profile

have been compared to available parameter sets from other projects in the central part of Amsterdam. They generally show a good agreement. For the calculations the mean values of stiffness have been taken whereas for the strength the low representative values apply. Table 1 contains the soil parameters for the Hardening Soil material data set.

The cross section shown in Figure 2 has been modelled in Plaxis 2D using the plane strain model consisting of a mesh of triangular elements with 15 nodes. In total 89 clusters have been defined. The generated mesh contains1906 elements. A picture of the model geometry is shown in Figure 4.

Due to the considerable length of the cross section only part of it has been modelled in order to reduce the number of elements and calculation time. The western court yard with its sloping bottom has been entirely included in the model geometry; however only one symmetric half of the eastern court yard has been taken into account. The distance between the boundaries on the left and the right side of the model geometry is 100 m. The bottom level is set at NAP -30 m; the top level at NAP +0,0 m. No existing structural elements such as foundation piles, foundation beams or floors have been modelled. Hence, the model considers a green field calculation in which the stiffness of these elements is neglected. This is a conservative approach regarding the expected differential deformations of the adjacent structure. Existing loads from the building on the stiff sands at pile tip level have however been taken into account.

The sheet pile walls (three in number) have been modelled as a beam element with the characteristics of AZ 18 profiles. The piles of the underwater concrete floor are loaded by tensional forces during pumping dry the building pits. Anchor elements and geotextile

Table 1. Hardening Soil parameter set

ID	Name	Type	γ_{unset} [kN/m³]	γ_{set} [kN/m³]	k_x [m/day]	k_y [m/day]	E_{50}^{ref} [kN/m²]	E_{oed}^{ref} [kN/m²]	E_{ur}^{ref} [kN/m²]	c^{ref} [kN/m²]	φ [º]	ψ [º]
1	1st sand layer	Drained	19,8	19,8	1,3E+01	1,3E+01	35000	20000	100000	1,0	33,0	3
2	2nd sand layer	Drained	19	19	8,0E+00	8,0E+00	32000	25000	80000	1,0	33,0	3
3	Allerod	Undrained	18,5	18,5	2,6E+00	2,6E+00	15000	9140	30000	3,0	28,0	0
4	Hollandveen	Undrained	10,5	10,5	1,7E-03	8,6E-04	2200	1187	8817	12,1	18,2	0
5	Top layer	Drained	17	18,4	8,6E-01	8,6E-01	17000	15000	50000	1,0	27,0	0
6	oude zeeklei	Undrained	15,4	15,4	1,3E-04	1,3E-04	9400	5429	20000	2,8	27,4	0
7	wadzand	Undrained	18,1	18,1	8,6E-03	8,6E-03	11600	4904	25000	2,0	34,9	4,9
8	Hydrobiaklei	Undrained	14,7	14,7	9,0E-05	9,0E-05	5700	3791	11400	13,3	23,3	0
11	basisveen	Undrained	11,7	11,7	1,0E-03	1,0E-03	2000	1004	7000	6,0	21,0	0

ID	Name	k_{ur} [-]	p^{ref} [kN/m²]	Power [-]	$K_{o:nc}$ [-]	c_incr [kN/m³]	y^{ref} [m]	P_f [-]	T-Strength [kN/m²]	R_{inter} [-]
1	1st sand layer	0,2	100	0,5	0,40	0	0	0,9	0	0,67
2	2nd sand layer	0,2	100	0,5	0,46	0	0	0,9	0	0,375
3	Allerod	0,2	100	0,5	0,50	0	0	0,9	0	0,67
4	Hollandveen	0,15	100	0,72	0,69	0	0	0,9	0	0,5
5	ophooglaag	0,15	100	0,8	0,55	0	0	0,9	0	0,67
6	oude zeeklei	0,15	100	0,57	0,54	0	0	0,9	0	0,67
7	wadzand	0,2	100	0,75	0,43	0	0	0,9	0	0,67
8	Hydrobiaklei	0,15	100	0,59	0,60	0	0	0,9	0	0,67
11	basisveen	0,2	100	0,8	0,65	0	0	0,9	0	0,5

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Continuation

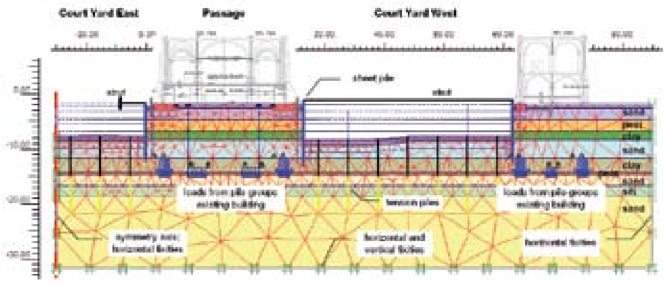

Figure 4. Model geometry

elements have been chosen to model the tension piles. The tensional stiffness of these elements has been adapted as to match the stiffness of the line of piles by dividing the axial pile stiffness by the center-to-center distance of 2,5 m of the piles.

Construction phases

Table 2 shows the construction phases with a short description. Except for the consolidation phases, all phases are of plastic analysis type. Consolidation phases have been defined in order to allow for dissipation of excess pore (under)pressures that develop during excavation.

Risk assessment of influence on the existing building and its foundation

The calculated greenfield deformations are used to access the influence on the existing Rijksmuseum building. The following aspects are considered:

- Horizontal soil displacements can cause lateral pile loading affecting the bending capacity of the existing wooden foundation piles of the Rijksmuseum.
- Vertical soil displacements on surface and pile toe level (1st sand layer) can cause pile and consequently (differential) building deformations. Vertical soil displacement at surface level needs to be controlled because settling soil may lead to an increase in negative shaft friction on the existing wooden foundation piles.
- Reduction of effective stress at pile tip level due to the excavation may lead to reduced bearing capacity of the end-bearing piles of the Rijksmuseum close to the excavation.

These aspects are analysed with numerical, analytical and empirical prediction methods in order to quantify the damage risks.

Results

For all main construction stages the following relevant deformations and stresses have been read from the output:

- horizontal deformation of the sheet pile wall;
- horizontal and vertical deformations in a horizontal cross-section at surface level;
- vertical deformation in a horizontal cross-section at pile tip level;

Table 2: Overview of construction phases

Phase	Description	Soil behaviour
foundation load on and load passage on	loads from pile groups and load of passage activated (historic higher surface level)	drained
load passage off	load of passage deactivated in accordance with actual surface level	drained
sheet pile walls on	beams activated; reset displacements from previous stages to zero	drained
East: strut +0,0; excavation -2,6; water level -3,8	strut court yard east activated; lowering of water level in eastern pit to NAP-3,8 m and excavation to NAP-2,6m (this dry excavation step is necessary due to the soil decontamination in the above layers)	undrained
West: strut +0,5; excavation -2,6; water level -3,8	strut court yard west activated; lowering of water level in western pit to NAP-3,8 m and excavation to NAP-2,6m (this dry excavation step is necessary due to the soil decontamination in the above layers)	undrained
consolidation 21d	consolidation phase, 21 days	consolidation
water level -0,8	water level in both pits rises from NAP-3,8m to NAP-0,8m	undrained
East: excavation -7,0; water level -0,8	Final excavation pit east to NAP-7,0m; water level in pit remains NAP-0,8m	undrained
West: excavation -7,7/-7,0; water level -0,8	Final excavation pit west to depth of NAP-7,0m to NAP-7,7m; water level in pit remains NAP-0,8m	undrained
consolidation 30d	consolidation phase, 30 days	consolidation
East & West: underwater concrete	underwater concrete clusters activated and material set applied	undrained
East: pump dry	water in pit east is removed	undrained
West: pump dry	water in pit west is removed	undrained

- modification of effective soil stresses near pile tips of the existing piles of the Rijksmuseum.

Figure 5 shows the deformed model and the contourplot of the deformations in the fully excavated situation.

Figure 6 shows the lateral deflections of the sheet pile wall in different stages of the excavation.

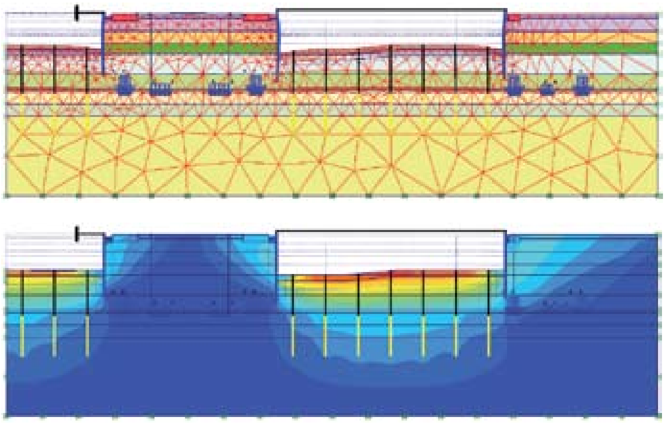

Figure 5. shadings plot of total deformations in final construction phase

The calculated maximum deformations are summarized in Table 3.

These greenfield results are translated to the pile foundations and the adjacent building of the Rijksmuseum in order to quantify the impact on the adjacent structrure. The maximum cumulative deformation due to the different sources is predicted to be 5mm and the angular distortion along the building is restricted to be 1/3000. The risk of damage at the masonry structures is negligible and the bending capacity of the wooden piles is sufficient in order to withstand the additional lateral pile loading due to the excavation.

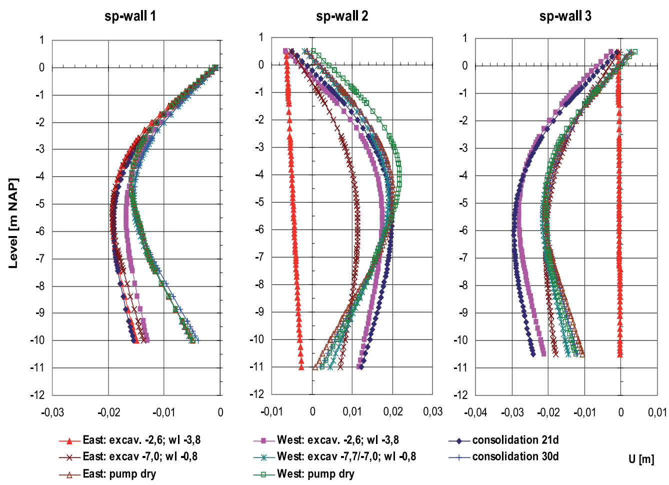

Figure 6. Lateral deformation of the sheet pile wall

Conclusion

In order to predict soil deformations in the vicinity of two excavation sites that are located inside the monumental building of the Rijksmuseum in Amsterdam extensive PLAXIS calculations have been performed. The design of the excavation of the building pits with an underwater concrete floor is predicted to cause an acceptable influence on the adjacent structure. The locations and the extent of the monitoring of the building and the sheet pile wall was derived from these risk analysis. The performance of the construction work on the adjacent building will be frequently compared with the predicted deformations in order to be able to anticipate in time with regard to unexpected deformation trends during the construction process.

References:

[1] A.M. De Roo, H.D. Netzel, P.J.M. Den Nijs; "Omgaan met risico's bij de renovatie van Het *Nieuwe* Rijksmuseum"; in Dutch; journal GEOTECHNIEK edition 3, juli 2006.

Acknowledgments:

The project organisation "Het *Nieuwe* Rijkmuseum" is greatfully acknowledged for providing the permittion to publish this article.

Table 3: maximum deformation

Type and location	Value
Maximum horizontal soil displacement at surface level at the location of the piles of the existing building (at closest distance to the sheet pile wall)	17mm
Maximum surface settlement at the location of the piles of the existing building (at closest distance to the sheet pile wall)	12mm
Maximum settlement on pile toe level at the location of the piles of the existing building (at closest distance to the sheet pile wall)	2mm
Maximum lateral wall deflection of the sheet pile wall	29mm
Reduction of vertical effective soil stress at at the location of the pile toes of the existing building (at closest distance to the sheet pile wall)	15%