Post construction settlement of the Port of Rotterdam seawall derived from the subsidence monitoring for the Q16 gas reservoir exploitation.

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Abstract

The decision by Oranje-Nassau Energie BV to install deep-anchored next to surface benchmarks in the zone of influence of the subsidence depression related to the exploitation of the Q16 gas reservoir provided a unique opportunity to analyse the post-construction settlement of the latest man-made harbour reclamation in the Port of Rotterdam. The reclamation included a large seawall embankment. Although the design of the reclamation and seawall construction takes into account a calculated settlement based on estimated parameters, the actual post-construction settlement had not previously been monitored. The results of the monitoring give an insight in the actual settlement parameters of the clay layers present along a large part of the Dutch coastline, and increase knowledge of this phenomenon which can be applied to the design of future seawall construction projects. These can be expected in view of the projected sea level rise.

Introduction

In the North Sea near the reclaimed Maasvlakte harbour, Orange-Nassau Energie extracts natural gas. As a result, part of the Maasvlakte (Maasvlakte 2) subsides. In order to analyze the amount of subsidence in the Maasvlakte, and predict its future development the consolidation and compaction parameters of the entire Maasvlakte subsurface column must be determined. The reclamation of Maasvlakte 2, including the construction of a large seawall was completed in March 2012. As a result of the reclamation, the subsoil of the Maasvlakte has subsided. The reclamation work started in 2008. During that work, the subsoil sank simultaneously. The subsidence during and after reclamation has not been monitored. In April 2014 gas extraction in the Q16 gas reservoir started, adding a reservoir compaction-related component to the subsidence of the Maasvlakte 2. This paper focusses on the non-exploitation related contribution of the ongoing shallow subsidence to the total subsidence prediction.

Methods

In anticipation of the exploitation of the Q16 gas reservoir several deep-anchored and surface benchmarks were installed in 2014 and the measurement of the level at various locations in the Maasvlakte started. The measured levels up to April 2016 were fitted to the NEN-Koppejan soil settlement model (CUR, 1996) to determine the settlement parameters.

For the purpose of the fitting analysis, use was made of the measured levels of the benchmarks installed at the navigation light on the seawall crest. This location was chosen as it is the closest land point with respect to the reservoir centre and subject to the largest preload as a result of the reclamation. Levelling was done using the nation-wide differential GPS network 06-GPS. A simplified representation of the subsurface was used in the analysis: the consolidation was assumed to be confined to the holocene Velsen Clay and pleistocene Waalre Clay between the sand body of reclamation and sea wall and the compact pleistocene and pre-pleistocene sand substrate in which the deep benchmark was anchored.

Location and data of the subsidence measurements

The measurement location is between national grid coordinates X = 59000 and X = 60000 (see detail 2 in Figure 1). Benchmarks were installed on the inner toe of the seawall. Three surface benchmarks (036F0001, 036F0002 and 036003) and one benchmark (Mb0002) anchored in the deep sand layer at approx. NAP-70m.

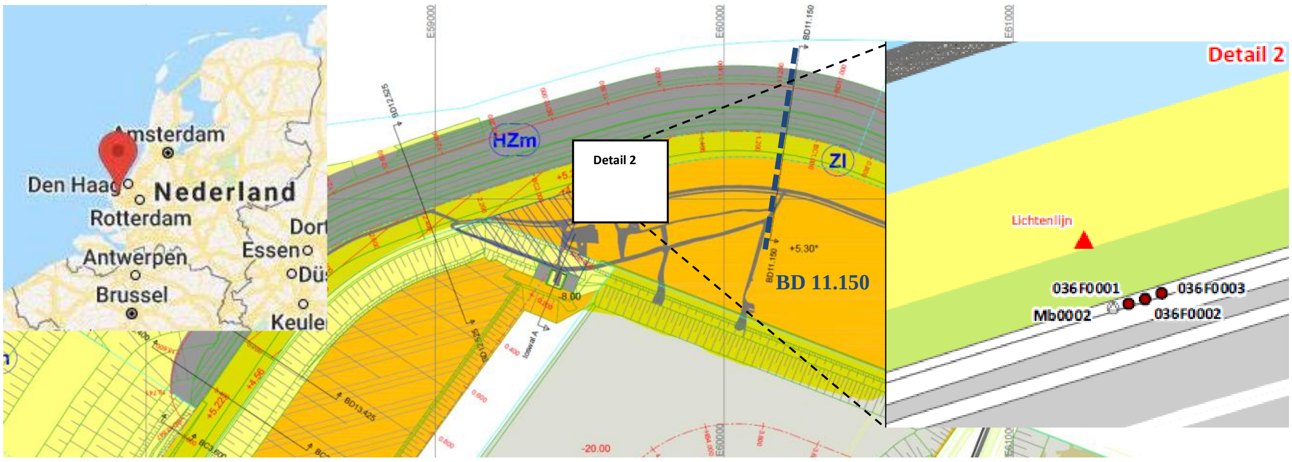

Figure 1   Location of measuring benchmarks. The length of the design construction profile BD 11.150 is 750 m.

Because the exact pre-construction seabed level is unknown at the benchmark location, the fitting analysis was carried out on two adjacent construction profiles of the seawall design. Profile BD 11.150, highlighted in Figure 1 is shown in Figure 2.

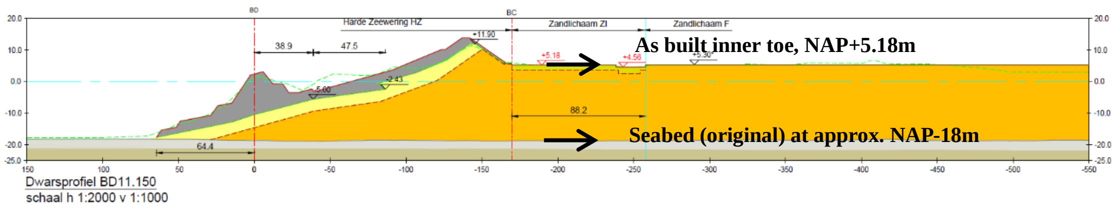

Figure 2   Realized construction profile BD11.150. The light blue layer represents the holocene Velsen Clay. The pleistocene Waalre Clay lies at a depth of ca. NAP-50 m

Monitoring data

The monitoring data at the benchmarks are shown in Figure 3. The behaviour of the deep benchmark is assumed to solely represent the subsidence related to the gas extraction. The difference of the surface and deep benchmark settlement is thus taken to be the contribution of the post-reclamation compaction of the Velsen Clay (thickness ca. 2 m) and Waalre Clay (thickness ca. 1 m).

Time steps in the settlement fitting analysis

The following timetable was derived from the reclamation and subsidence monitoring data:

- The start time of the reclamation work is 1 December 2008.
- Construction was completed 1 March 2012.
- As-built surveying was carried out on 14 March 2012.
- The starting time of the settlement monitoring is 27 January 2014.
- Monitoring data up to and including 25 April 2016 were used.

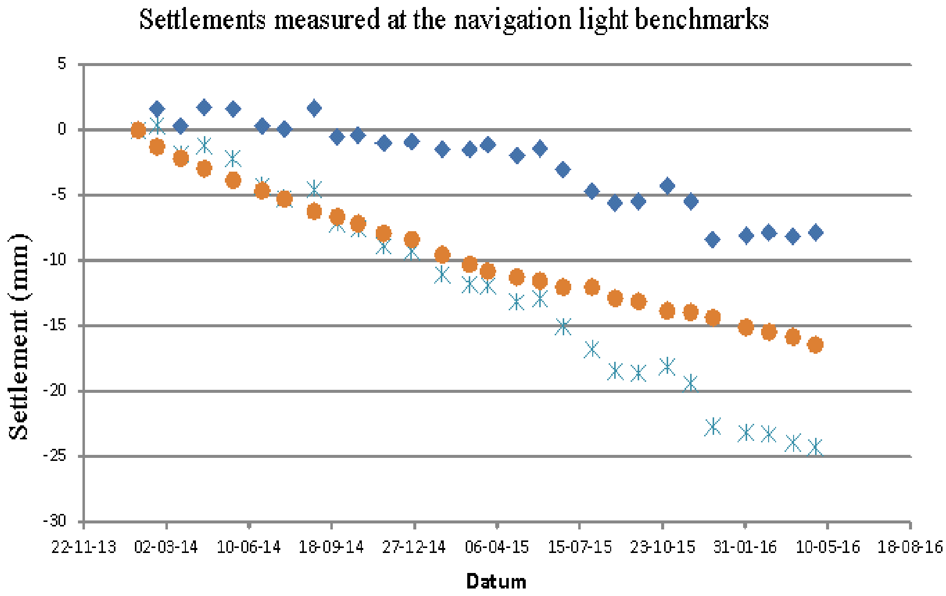

Figure 3 Settlement curves relative to start of monitoring (zero point, January 2014) of deep (squares) and the average of the surface benchmarks (crosses). The dotted line is the difference.

Settlement fitting calculation and analysis

Settlement modelling

The settlement model used is the NEN-Koppejan model with Darcy-consolidation using the commercially available D-Settlement program package (Deltares, 2021). The effective soil pressures were calculated assuming that the initial piezometric head for all layers is equal and at average sea level (NAP+0m). This assumes that a hydraulic equilibrium was established since deposition relative to the piezometric change caused by the surcharge. The loading scenario applied in the model assumed a uniform load increase on the seabed with time (1 December 2008 - 1 March 2012). The load increase was applied in monthly timesteps. At the end of the construction an additional load was applied to compensate for the anticipated settlement during construction.

Settlement fitting is performed in the D-Settlement program as an iterative process. Subsidence monitoring was carried out when the subsoil was still consolidating. In the calculation we use the seabed level as reference level, assuming that the settlement of the constructed ground is negligible. Because the precise seabed level prior to the loading and at the start of monitoring is unknown (i.e. was not measured), the first iteration determines the approximate position of the measured levels on the settlement curve (the tail of Figure 4). After that, the settlement fitting analysis proper can be carried out. During the iteration the settlement parameters are adjusted until a difference of less than

1% between measured and calculated values is reached. Only the settlement parameters of the clay layers (Velsen and Waalre clays) are adjusted.

Result of settlement fitting

The final result of the fitting iteration for profile BD 11.150 is shown in Figure 4. The applied loading and calculated settlement curves are shown with the measured settlement expressed in red. At convergence, a total settlement of 0.971m was calculated. It should also be noted that the monitoring since 2014 represents the secondary (post-hydrodynamic) consolidation phase.

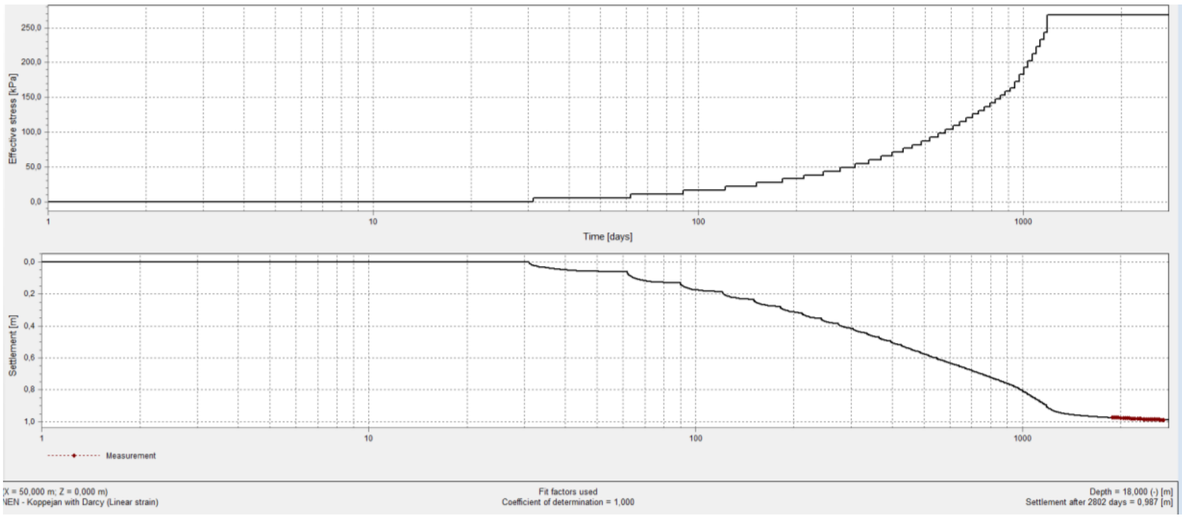

Figure 4 Fitted settlement at design profile BD11.150. The red line at the tail marks the monitoring data.

The result of the settlement fitting is as follows:

Layer		Volumetric weight $[kN/m^3]$	Cp [-]	C'p [-]	Cs [-]	C's [-]	Overconsolidation Ratio [-]	Consolidation coefficient $[m_2/sec]$
Velsen clay	initial	14	15	7	160	80	1,3	1e-6
	adjusted	14	19,25	8,81	160	103,85	1,28	1e-6
Waalre clay	initial	17	2,7	25	400	500	1,3	1e-7
	adjusted	17	3,47	31,45	400	649,05	1,28	1e-7

Table 1 Adjusted settlement parameters for clay layers at profile BD11.150 (original seabed at NAP-18m).

The derived settlement parameters depend on the loading schedule. The settlement parameters may differ if a different load scheme is applied. The fitted parameters indicate that the clay layers behave stiffer than estimated on the basis of the recommended values in the building code, which are based on a large number of laboratory tests on samples from the mainland. A geological explanation is lacking at present, but the difference in scale and time between laboratory conditions and the real world may well explain the difference. In any case it appears that using the recommended values from the building code is a conservative approach to the design.

Conclusion

The applied analysis of deep and shallow subsidence monitoring data that were primarily meant for the control of the exploitation of a near-shore gas reservoir provided a rare and unique opportunity to determine the in-situ consolidation parameters of the clay layers in the subsoil of a primary seawall in the Port of Rotterdam Maasvlakte-2 extension. It is expected that the projected sea level rise demands a future upgrade of the coastal defence. The obtained insight in the actual settlement behaviour contributes to the design of future seawall constructions along the Dutch coast by for the first time providing realistic parameters for clay layers that are common in the subsoil along the Dutch coast.

References

CUR, Centre for Civil Engineering. (1996) Building on Soft Soils. London, Routledge, 500 pp.

Deltares (2021). D-SETTLEMENT, Embankment design and soil settlement prediction; User Manual, 312 pp. (https://download.deltares.nl/en/download/geotechnical-software/)