Fort Sint-Filips 2022

Integrated Soil remediation – nature restoration – Flood defence & Harbor infrastructure project

Eds. Astrid Verheyen &
Michaël De Beukelaer-Dossche

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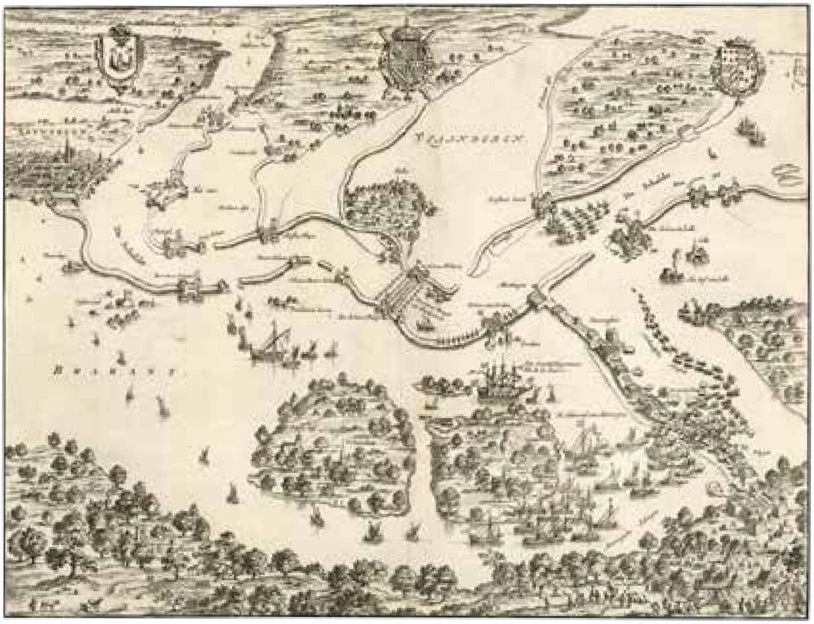
History

Scheldt/Harbour

The importance of the Scheldt for the foundation and development of Antwerp cannot be overstated. The river was the lifeline for the city and its direct gateway to the sea. From this strategic position, the small trading settlement grew into a genuine trading metropolis in the 16th century. Forts and entrenchments were erected along the Scheldt at strategic locations in order to defend the city. The city, as well as the Spanish and State armies, built many fortifications. Later, these forts were modernised during the Austrian, French, Dutch and finally Belgian periods **[Img. 01-03]**. After all, an enemy fleet could use the river to attack trading installations or ship in troops.

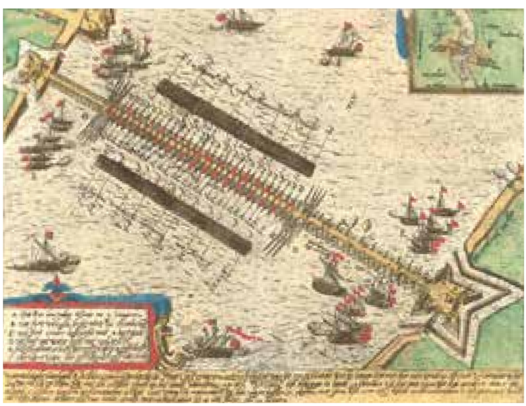
Today, we are familiar with the forts of Lillo and Liefkenshoek, Sint-Marie, Burcht and Fort Filip, each with a fascinating story.

Img. 01 Illustration of the surroundings of Antwerp and the Scheldt around 1584. It shows the different forms of protection on and around the Scheldt that were used at the time. In the centre, we see Fort Sint-Filips. At the time, it was still connected to Fort Sint-Marie by a bridge.



Img. 02 Map of Ferraris, 1771-1778.

Img. 03 Forms of protection on and around the Scheldt.



Fort Sint-Filips
16th century –
20th century

Two different forts were built on this bend in the river Scheldt: the 16th-century Fort Sint-Filips and the 19th-century Fort Filip. During the turbulent 16th century, the Revolt of the Netherlands, known as the Eighty Years' War (1568-1648), broke out. There were political and religious tensions in many cities and regions, and resistance to Spanish rule under Philip II grew. The Scheldt forts have their origins and saw their greatest expansion during this conflict. When the Spanish armies were driven out of Antwerp and a Calvinist government was established, the city built the twin forts of Lillo and Liefkenshoek (1579-1584) at the instigation of William of Orange.

Spain, meanwhile, had begun a campaign of conquest in the Netherlands and had a formidable army commander and strategist, Alexander Farnese, Duke of Parma. To cut off the city from the forts of Lillo and Liefkenshoek, he built the Sint-Marie and Sint-Filips forts and set up a blockade on the Scheldt in July 1584. In a few months and with the help of Italian engineers, he managed to completely block the northern passage and supplies to the city. He had a 720-meter-long pontoon bridge built that completely closed off the river at Kallo. For this purpose, more than 10,000 trees were felled in the Waasland area and 1,500 ship masts were brought from Denmark. A bridgehead was constructed on both banks of the Scheldt, between which 32 ships were anchored, chained and covered with a boarded floor. On either side of the bridge was a defensive line of 33 fortified barges, equipped with pointed Danish masts to keep ships at bay.

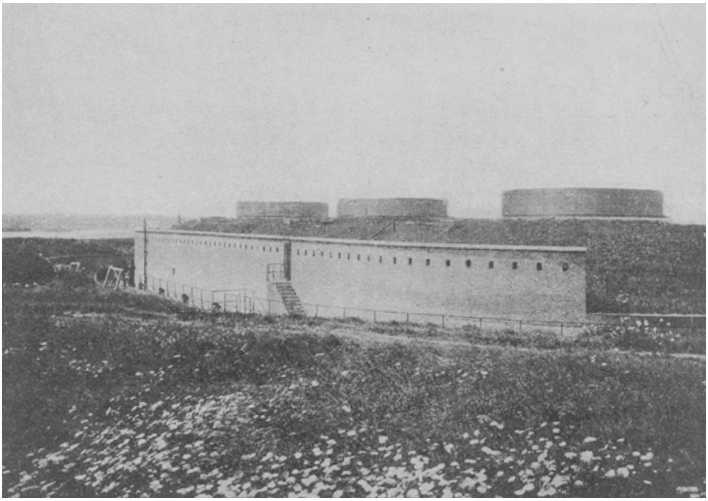
Farnese's bridge [Img. 04] held the city in a stranglehold for months. The people of Antwerp tried to blow up the bridge with the bomb ships 'Hoop' and 'Fortuin' but failed. After months of rebellion and siege and after the battle of the Kauwenstein dike that ended in failure for Antwerp, the city surrendered. Mayor Marnix van Sint-Aldegonde negotiated the surrender at Singelberg on the Left Bank. This capitulation marked the end of Calvinist rule in Antwerp and is referred to as the Fall of Antwerp.

In 1789 the fort was dismantled, but the site remained in use. Among other things, there was a customs post, a church and an inn. The fort was alternately owned by private individuals and by the polder administration.

Because the 19th-century Fort Filip was built on top of it, nothing of Fort Sint-Filips was visibly preserved. It was a square sconce with four bastions and a bridge across the moat in the direction of Antwerp. The new construction now includes some ramparts and bastions as a reminder of the fort. At the start of the Farnese Bridge, a projection was made into the Scheldedijk. The battle at this float bridge, an important episode in the history of the Netherlands, is thus made tangible.

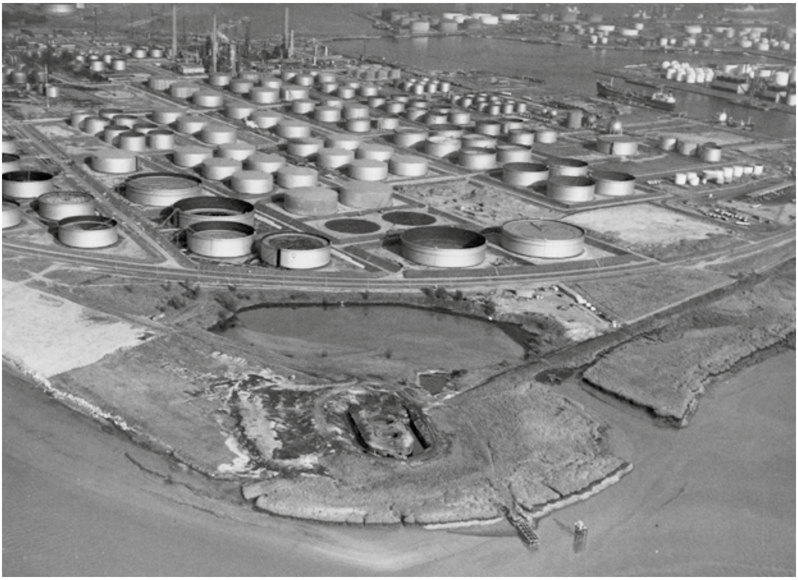
In 1870, the fort was purchased by the War Department, which built a new fortification there as part of the Brialmont ramparts in the period 1870-1881. This Fort 'Filip' had a completely different layout: it consisted of an elongated, brick building with three turrets and a dry moat. In each turret were two heavy guns aimed at possible warships on the Scheldt [Fig. 05]. Just before World War I, Fort Sint-Filips became part of the city's second line of defence. Three new coastal batteries (Blauwgaren, Wilmarsdonk and Kruisschans) were provided for the expansion of the first-line defences. At the fall of Antwerp in 1914, Belgian troops destroyed the turrets as they retreated so that they could not be used by the Germans. During WWI the fort was not operational, nor was it during WWII.

In the 1950s and 1960s, the site was used for dumping and burning waste, initially in the open, then (partially) in a trial incinerator. At the time, several players within the port of Antwerp were struggling with a waste disposal problem, for which the fort had to provide a (temporary) solution. At that time, it was 'the only acceptable place on city land (sic)' and 'a properly secluded place where burning could be carried out without disturbance'. By establishing the fort as a dumping and incineration site, the city wanted to provide an opportunity for ship maintenance/repair companies to dispose of their waste oil. However, the supply would not remain limited to petroleum waste from the ship restorer's federation. Other companies and agencies were disposing their waste products there too. Finally, the Port Authority of the city of Antwerp also used the site [Img. 06]. The oil that was skimmed from the surface water in the docks was taken to the fort for burning. Historical documents show that from 1959 to 1970 (waste) products were delivered



Img. 04 Bridge of Farnese.
Img. 05 Fort Sint-Filips with the three gun turrets.

Img. 06 Aerial views of the port area and Fort Sint-Filips in 1969.



to this zone, originating from various companies in the Antwerp port, from moored ships, the city of Antwerp and the army. The supply of this waste to Fort Filip was monitored systematically but historical documents show that despite the monitoring, a great deal of illegal dumping still took place in and around the fort area. The fort was permanently closed on October 1, 1970. The site was covered with dredged sediment in the 1970s. What remained of the fort until spring 2020 was largely under sand or water. Right next to the fort was a buffer basin through which, with the approval and knowledge of the city of Antwerp, since 1950 (purified) rain and wastewater from the adjoining company and its predecessors was discharged. This buffer basin was and still is connected to the Scheldt, so that at low tide the treated and purified wastewater from the buffer basin flows into the Scheldt. The buffered water was analysed at regular intervals and, if necessary, buffering could be stopped at a moment's notice. Throughout history, several actors have contributed to the contamination, which has now been assessed using current knowledge, revealing a remediation need .

The 1958 idea to turn this location into a tourist centre remained shelved for a long time because of the contamination present. In 2021, the domes of the fort will be visualized in the above-ground construction and the fort will be highlighted to visitors.

1 Havermans, R. Historisch-geografische sprokkelingen uit het Antwerpse polderland, 521 – 523.
2 Havermans, R. Historisch-geografische sprokkelingen uit het Antwerpse polderland, 524.
3 Havermans, R. Historisch-geografische sprokkelingen uit het Antwerpse polderland, 531.
4 Gils, Vesting Antwerpen. 3 : Schelde- en redeverdediging 1838 – 1944, 65-69.
From study work carried out in 2014 and 2015 for the Port of Antwerp by Geheugen Collectief vzw

B

Objective

Sigmaplan
A Flemish answer to protection against North Sea storm surges

The disastrous floods of 1953 and 1976 made it clear that Flanders needed to better protect itself from storm surges from the North Sea. To ensure safety in the Sea Scheldt basin, the Sigmaplan was drawn up at the Flemish level in 1977. This plan provided for the raising and strengthening of the dikes and the creation of thirteen controlled flood plains. At least 512 km of dikes have been raised to Sigma height in the meantime. The final (and most challenging) dikes will be completed in the following years. Thirteen flood zones in Flanders, of which Kruibeke-Bazel-Rupelmonde is the largest, have been proving their worth for years now.

Rising sea levels and a contemporary approach on integrated and sustainable water management prompted an update of the original Sigmaplan in 2005. Beside building dams against flooding we need to give more room for the river. The Flemish Waterways Authority (formerly Waterwegen en Zeekanaal) therefore started work on the construction and design of additional flood areas along the Scheldt and its tributaries that can temporarily store large volumes of water during a storm surge. DVW works closely with the Agency for Nature and Forests in this context. In fact, the Sigmaplan **[Img. 07 & 08]** has multiple objectives. In addition to reducing flood probabilities, it also aims to restore the natural characteristics of the river. Full implementation should be completed by 2030, after which another round of evaluation is planned.

Comprehensive Flemish-Dutch

The Flemish Sigmaplan is not a stand-alone project. The 2005 plan is part of the process of drawing up and realising the long-term vision (LTV) of the entire Flemish-Dutch Scheldt estuary (Development Plan 2010), in which work is done to create a more safe, accessible and natural Scheldt. After all, the Sigmaplan and the 2010 Development Plan influence each other and the partners involved therefore exchange information with each other on a regular basis. Information from various preliminary studies and supporting studies in previous years has shaped the Sigmaplan throughout the years. Thus, the information needed to create workable plan alternatives and to actually evaluate these alternatives came largely from these preliminary studies.

The 2005 Sigmaplan EIA (environmental impact report) and SCBA (social cost-benefit analysis), carried out in parallel while interacting with similar studies at the estuary level of the 2010 Development Plan, provided an early apprehension on the form that an optimised Sigmaplan (with flood safety as its objective) should take. These general principles (essentially a preference for the Room for the River (RvR) concept) were therefore adopted in the Development Plan 2010 (OS 2010), drawn up by the project organisation ProSes as part of the Flemish-Dutch Scheldt Commission.

However, the 2010 Development Plan not only makes statements about the realisation of the safety projects on Flemish territory, but also about the way in which the 'naturalness' pillar of the LTV should be shaped. This nature development plan [Fig. 01] has a very close relationship with the Sigmaplan in Flanders, because both safety and naturaleness are often combined in the same areas. For this reason, the Flemish Government decided to include the pillar 'naturalness' from the Development Plan 2010 in the Sigmaplan, so that the objectives of this plan were extended from just safety (with the subsidiary objective of naturalness) to two equivalent objectives: safety and naturalness. How these objectives of safety and naturalness were developed and the integration step that was taken to arrive at the Sigmaplan is explained below.

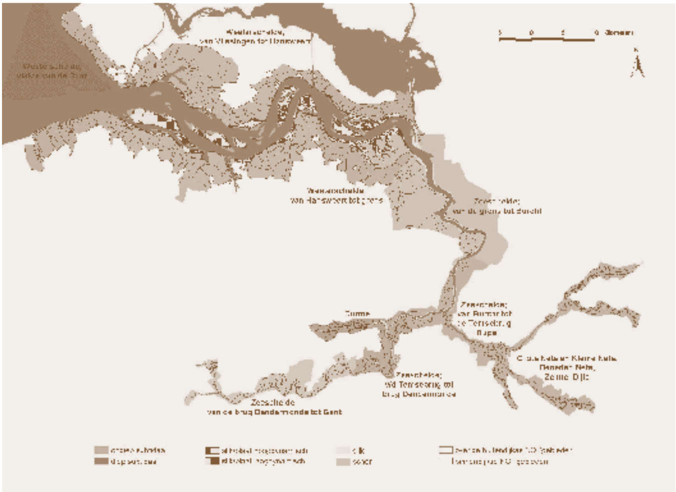
The (Flemish) risk methodology (UGent in collaboration with WL): input for SCBA, from protection to damage limitation

With the updated Sigmaplan, Flanders no longer opts for protection against a water level with a certain probability of occurrence, but for limiting the damage that can occur. For this purpose, the concept of 'risk = probability x damage' is used. The updated Sigmaplan aims to realise an acceptable flood risk along the Scheldt and its tributaries. This acceptable flood risk was established based on a consideration of the social costs and benefits, called a social cost-benefit analysis (SCBA).

Using the hydraulic model of the Scheldt estuary, several scenarios were studied in which POGs (potential flooding areas) were combined with each

Img. 07 Example of a Sigmaplan project. Works on the Scheldt quays at Sint-Andries and Het Zuid.

Img. 08 Example GOG-GGG Bergenmeersen with nature infill in Wichelen.



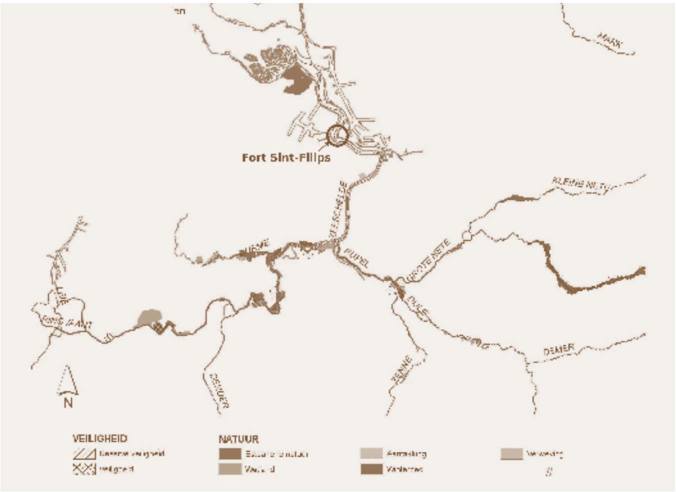


Fig. 01 Nature Development Plan.
Fig. 02 Most desirable alternative

other and dikes were raised and locally even lowered in order to give more room to the river. Storm surge barriers and an 'Overschelde' (connection between Western and Eastern Scheldt) were also considered.

Optimisation of the Sigmaplan 'safety' using the SCBA method

After determining the best solution 'dike raising and room for the river', the optimal plan had to be found through a step-by-step optimisation procedure, systematically comparing the many possible variants based on their social costs and benefits. The optimal Sigmaplan 'safety' that was compiled based on the method described above was ultimately defined as follows:

- finishing the zero alternative (Sigmaplan 1977);
- 24 km of additional dike elevations in the vicinity of Antwerp;
- the creation of 1,325 ha of new floodplains.

Sigmaplan 'naturalness'

In its meeting on 17 December 2004, the Flemish Government decided to approve the proposed decisions of the Development Plan 2010 and the main points of the updated Sigmaplan.

In order to sufficiently contribute to the realisation of the objectives of the long-term vision for the Scheldt estuary as far as the naturalness component is concerned, additional nature development projects were deemed necessary. Building further on the existing ecological research - carried out via the plan EIA, the SCBA, the LERs (agricultural impact report) - a multi-pronged ecological study was carried out by the University of Antwerp and the Institute for Nature and Forest Research (hereinafter referred to as INBO).

The multipronged approach involved selecting those habitats for which the river in question has regional or Europe-wide importance. For these habitats in particular, the potential for achieving conservation objectives was explored. The existing natural values of the valley areas were examined and it was determined where they could be enhanced. At the same time, the potential for the different nature types in theses areas were modelled based on abiotics and connectivity. The expertise of the Agency for Nature and Forests were also included in the considerations. A final approach was the functional one. In the process, the chemical, physical and biological bottlenecks of the rivers themselves were examined and translated into necessary adjustments.

The final most preferential layout based on all tracks was discussed at length and established after consensus.

Synthesis of the Sigmaplan: safety and naturalness

On the existing preferred scenario 'safety' and knowledge of the priority areas and their design from the point of view of 'naturalness', a synthesis proposal could then be drawn up. At the request of the agricultural sector, not one but three synthesis proposals were drafted so that more than one choice would remain; the sector could then express itself based on a consideration of its interests. The three synthesis proposals each met the following conditions:

1. they are comparable to the optimal safety alternative in terms of net safety benefits;
2. they each meet expectations in terms of 'naturalness' (i.e. guaranteeing 'robust' nature in the estuary while meeting the estuary's conservation objectives), albeit in different ways.

Three tests were conducted for each of the three synthesis proposals: a nature test, a safety test, and an agricultural test. These tests were conducted by experts for each of the three "sectors" and amounted to a ranking of the three synthesis proposals according to relative preference. These tests showed that both the agricultural and nature sectors preferred scenario 1 because of the separation of functions, the higher quality for both agriculture and nature and the fact that, in net terms, less agricultural land had to be taken up. Additional comments from the agricultural sector regarding the selection of individual areas were also considered, where possible, in the formulation of the final "most desirable synthesis alternative," which is a derivative of the original Scenario 1.

Most desirable alternative

A map of the final proposed most desirable plan alternative, prepared using the method outlined above, is presented on page 30 **[Fig. 02]**. The implementation of the updated Sigmaplan was finally laid down in a decision by the Flemish Government in 2005 and 2006.

ref. Flemish Dutch Scheldt Commission: http://www.vnsc.eu; planMER updated Sigmaplan non-technical summary: http://www.lne.be; merdatabank/uploads/merntech177.pdf; General Methodology extreme water conditions; Bergenmeersen project book; Risk methodology WL; Functioning of estuary UA; Nature development plans INBO

Soil Remediation

OVAM - ABO - TALBOOM

As a result of landfilling and burning of waste from the 1950s to the 1970s, the site became severely contaminated. Based on the soil surveys conducted, very extensive contamination was identified in both the solid part of the earth and in the groundwater in the fort zone and the sediment at the level of the buffer basin **[Img. 09]**.

The contamination present is historical in nature, and (largely) originated before the Flemish Soil Decree came into force in 1995. The severity of the contamination identified was such that remediation appeared necessary.

Remediation target

In determining the realistic remediation objectives, the requirements of the Flemish Soil Decree were taken into account. Since this is a historical contamination, the following regulations are taken into account:

§1. Soil remediation, in the case of historical soil contamination, is aimed at preventing soil quality from posing or having the potential to pose a risk of adversely affecting people or the environment, by using the best available techniques that do not entail excessive costs. In the event that the land is to be given a different use within the framework of a provisionally adopted draft construction plan or implementation plan, the soil remediation shall be aimed at avoiding that the soil quality poses or may pose a risk of detrimental effects on humans or the environment within this future use;

§2. If it is not possible to achieve the soil quality mentioned in §1 by using the best available techniques that do not entail excessive costs, the necessary usage or zoning restrictions shall be imposed;

§3. The selection of the best available techniques that do not entail excessive costs is done independently of the financial capacity of the person liable for remediation. The Flemish Government may determine the elements to be taken into account in concrete terms when evaluating the best available techniques that do not entail excessive costs.

Taking these assumptions into account, however, it must be concluded that, of all the remediation techniques that could be considered, none would be able to completely remove the risks. With the techniques that were considered technically feasible, it was not possible to tackle the pollution in the southern and eastern embankment between the fort and the Scheldt.

Instead of realising strict risk limits where there is no longer any risk from the contamination, the choice was made to reduce the risks. This can be achieved, depending on the remediation technique chosen, either through the removal of waste loads or isolation of the contamination.

Fig. 09 Soil remediation of the fort.
Fig. 10 Insulation material for the pond.

Pipeline Corridor

POA - ANTEA

The Port of Antwerp is the most important hub in the Western European pipelines. This extensive pipeline network offers chemical companies a safe, reliable and environmentally-friendly means of transport for the supply and distribution of products in Belgium and surrounding countries. They provide a stronger link between neighbouring businesses, other ports, industrial areas and the hinterland. The use of a pipeline corridor is gaining importance year after year and is part of the modal shift solution.

Pipelines also realise growth opportunities in the context of the energy transition, in which the Port of Antwerp is playing a key role. Pipelines are ideal for transporting hydrogen and CCS/CCU (CO2 capture and storage), for example, and are also essential for the construction of heat networks. Examples include the steam network Ecluse, which will supply energy to surrounding port companies using heat from six incinerators.

Within the (petro)chemical cluster in Antwerp, the industrial and independent tank storage operations are connected to each other via 57 different product pipelines or 1,000 km of pipelines that account for almost 90% of all transport of liquid goods within the port. However, this network needs to be further expanded.

Although these additional pipelines are a necessity for the continued operation of the port, the Port of Antwerp also realises that free space is scarce and that within that scarce space it must still make maximum efforts to:

- make room for new construction;
- clear passages and connections and keep them clear;
- build pipeline highways;
- keep pipeline networks well organised;
- bundle pipes to the maximum extent.

The pipeline area along the Scheldelaan is one aorta in the pipeline area in the Port of Antwerp. That existing pipeline zone is already full in the current situation.

Within the reconstruction works in this zone, additional space has therefore been created for the expansion and widening of one of the most important zones of the port's pipeline network. Near Fort Sint-Filips, the water barrier partly takes the form of a classic dike. However, where the site connects to Scheldelaan there is not enough room for this given the desired expansion of the pipeline zone. It was therefore decided to build a flood wall here instead of a wide dike.

C

Preliminary Research

Environmental Quality

ABO - TALBOOM

Initial sampling

In 2010, a site visit was performed for the first time as a function of an indicative soil investigation. The purpose of this is to determine whether there is a significant indication of the presence of soil contamination (soil and/or groundwater) as a result of the temporary and permanent dumping and burning of waste on the site since World War II.

The results of the exploratory sample surveys revealed strong contamination of both the solid part of the earth and the groundwater in the fort zone and the sediment of the drainage basin. Elevated concentrations of the parameter groups heavy metals, mineral oil, volatile aromatics (BTEX), chlorinated hydrocarbons (VOCs), polycyclic aromatic hydrocarbons (PAHs) and polychlorinated biphenyls (PCBs) were found.

Given the indicative nature of the soil investigation, it was concluded that additional research was necessary in view of the location of the site (nature reserve), the extent of the contamination, the probable presence of pure product in the form of both floating layers (LNAPL) with mineral oil and/or volatile aromatics and zinc layers (DNAPL) with VOCs, and the current threat of a spread towards the Scheldt.

Mapping the fort

Following the indicative soil survey, in the period 2010-2014, the soil remediation experts (Ecorem and later ABO nv) appointed by Port of Antwerp carried out numerous research efforts to map out the contamination; the extent and severity of this only increased as the survey progressed. A thorough site survey examined all possible entrances to the fort. An inventory was also made of the various rooms in the fort where water with an oil film and/or pure product (oil) was present. Black product was detected in the majority of the rooms examined. From the analysis results, this was found to be 97% oil.

In four successive phases of investigation, the further extent of the various contaminants was identified. Where technically feasible, contaminants were delineated into horizontal and vertical planes.

The concentrations of pollutants detected (including mineral oil, volatile aromatics (BTEX) and chlorinated hydrocarbons (VOCs)) were exceptionally high, leading to unprecedented situations when conducting the sampling:

- on a regular basis, the sampling equipment had to be cleaned by specialised firms because of the extremely high degree of contamination;
- when drilling through an existing clay layer in the subsurface in November 2013, accumulated gas escaped from the subsurface through the drill pipes. After an intervention by the fire department, the released gas was found to consist mainly of 1,1,2-trichloroethane and 1,2-dichloroethane, contamination parameters related to the contamination below the fort;
- groundwater sampling in the core of the contamination in/under the fortress revealed the presence of pure product quite quickly.

The samples taken contained three phases: groundwater, LNAPL (Light Non-Aqueous-Phase Liquid) and DNAPL (Dense-Non-Aqueous-Phase Liquid). The pure product concerns a combination of mineral oil, BTEX and VOCs. Saturated soil samples contained up to 30 percent by weight of VOCs and 53 percent by weight of mineral oil. It was suspected that the presence of pure product in the shallower soil layers was limited to the contours of the fort (approximately 5,500 m²). Presumably, the established sink layer just above the Boom Clay extends over an area of about 22,000 sq. ft.

The contaminated area has a horizontal extent of about 6 ha and vertically the contamination has penetrated to a depth of 30 m with the Boom clay providing an under-seal. An estimated 1.2 million m³ of soil is contaminated at this location. The combined exploratory and descriptive soil investigation of 2014 concluded that soil remediation was required for three contamination areas on the site:

- the contamination zone at the fort, delimited in vertical plane by the Boom clay;
- the contaminants located under the sediment and at the level of the banks of the buffer basin;
- a contamination core with BTEX and mineral oil north of the fort.

Human and ecological risks related to the contaminants as well as risks of further spread were identified. Therefore, the remediation need was described as very urgent. The following use recommendations were imposed in anticipation of the remediation work:

- maintaining the closure around the fort until the remediation works are carried out;
- a ban on the pumping and use of groundwater;
- a ban on any possible action in the subsurface at the level of the contaminated zone (excavations …) pending the remediation.

Buffer Basin

In 2016, a second descriptive soil survey was prepared for the sediment contamination present. The research site consisted of the buffer basin located south west of the bend in the Scheldelaan and a small pond located at the main entrance to the fort. Both surface water areas were separated at the time.

The treated wastewater from a nearby concession is buffered for further discharge into the Scheldt, in the buffer basin next to the fort. The discharge flow rate is in the order of 31,000 m^3/day. Water of unknown origin (presumably drainage from the Scheldelaan, but possibly also from nearby facilities) was also drained into the buffer pond at an unprecedented and not continuous flow rate.

The buffer basin is in contact with the Scheldt through a system of check valves. At low tide, the water level of the Scheldt is lower than the water level in the buffer basin. The valves on the effluent side of the basin then open and the water in the buffer basin can flow into the Scheldt. At high tide, the water in the Scheldt rises above the water level in the buffer basin. The valves on the effluent side then close and the water level in the buffer basin increases because there is no longer any outflow towards the Scheldt. As a result, the water level in the basin fluctuates considerably. At low tide only a limited channel is present and the rest of the basin is dry, at high tide the entire basin is flooded. The fluctuating water level was a major complicating boundary condition during the fieldwork.

Sampling in the ponds was conducted using a boat with limited draft (10 cm) [Img. 11]. Using a DGPS, the sampling locations could be accurately

Img. 11 Sampling in the buffer pond.

determined. The sediment was sampled there in different layers: the upper, less cohesive black silt layer; the firmer, lighter-coloured silt layer and the underlying peat layer. At three locations, drill pipes were drilled through the peat layer into the underlying tertiary sand.

Measurements from 2015 and 2016 were used as a basis for determining the extent of the sediment contamination. The Surfer® software package was used to interpolate the extent of the different layers in the sediment. The volume of the non-solid black silt layer was estimated to be approximately 21,000 m^3. The volume of the lower lighter coloured silt layer was estimated to be about 16,500 m^3. The underlying peat layer has an average thickness of 2.4 m resulting in a volume of approximately 57,000 m^3. Given the large amount of data and the grid-based survey approach, it was decided to interpret the buffer basin results using a geo-statistical method.

In general, it could be stated that both at the level of the small pond as well as at the level of the buffer basin, very highly elevated concentrations of mineral oil, BTEX, PAHs, VOCs, and chlorobenzenes occurred in the sediment. For all of these parameter groups, the soil remediation standard was exceeded by a factor of 10 to 100 (for some VOCs, even by a maximum exceedance factor of 290,000). A total pollutant load of 5,684 tons was estimated.

For the historical contamination with mineral oil, BTEX, PAHs, VOCs, heavy metals, chlorobenzenes, OCBs and PCBs in the sediment, remediation measures were considered necessary since it concerned severe soil contamination. Therefore, the remediation need was described as very urgent.

Soil Survey

BAAC - GEOTECHNICS

Archaeological

In preparation for the excavation, six landscape borings were carried out to 6 m below ground level from which the depth of the archaeologically relevant layers was determined. These relevant layers appeared to be below the level where excavations would be carried out. Further trial trenching or excavations were therefore not necessary.

In addition, in consultation with the archaeological service of the city of Antwerp, arrangements were made to highlight the fort to be remediated and the sixteenth-century fort located below it after remediation and when the site was redeveloped. In addition, the location of the Farnese bridge will also be provided with an information module that was developed in an earlier Interreg IVA cooperation project - 'Fort and Lines in a Border-wide Perspective' - and which highlighted the history of the State-Spanish Line (of which the sixteenth-century Fort Sint-Filips was part).

Geotechnical

When the geotechnical soil investigation was conducted by probing (continuous - 200kN) in 2009 and in 2013, the stratification of the zone's subsurface was mapped to 35 m below ground level. A total of 39 Cone Penetration Tests (CPT) were performed on the portion of the site that was accessible to the CPT truck at that time. In addition, 12 boreholes were drilled in the zone to take samples of the soil.

Hydrodynamics

WL

The presence of the contaminated Fort Sint-Filips made it impossible to implement the full area of tidal nature designated in the Sigmaplan. A dynamic side channel and erosion pit 6 m below the level of the Scheldt sediment near the bank was a cause of concern for the stability of the dike and the ecological development. To achieve a gradual transition to estuarine nature and to ensure stability, it was proposed to fill in this gully and pit. The Vlaamse Waterweg nv therefore commissioned Flanders Hydraulics and the INBO to investigate this further and to come to an optimal nature development that meets the requirements of the Sigmaplan.

A groyne was quickly put forward as a solution for the tidal nature, and after several iterations and simulations with the locally detailed hydrodynamic model Scaldis 3D, the design was concluded. Sustainability aspects such as avoiding high bed shear stresses and ensuring gradual transitions to avoid localised de-vegetation were taken into account to the maximum extent possible. Ultimately, a configuration at 3.5 m Second General Water Adjustment or TAW with one curved groyne was chosen to cut the side channel and allow for the development of high quality mud and low dynamic shallow water.

1 Schramkowski, G.; Van Oyen, T.; Verwaest, T.; Mostaert, F. (2015). Getijverandering door verondieping te Fort Filip (Tidal change due to deepening at Fort Filip). Version 4.0. WL Opinions, 14_066. Hydraulic Engineering Laboratory: Antwerp, Belgium

2 Maximova, T.; Smolders, S.; Beullens, J.; Vanlede, J.; Schramkowski, G.; Verwaest, T.; Mostaert, F. (2016). Verkennende studie kribben Fort Filip: Deelrapport 1 – historische studie en hydrodynamische modelresultaten (Exploratory study groynes Fort Filip: Part report 1 - historical study and hydrodynamic model results). Version 6.0. WL Reports, 15_042. Hydraulic Engineering Laboratory: Antwerp, Belgium

3 Maximova, T.; Smolders, S.; Schramkowski, G.; Verwaest, T.; Mostaert, F. (2016). Verkennende studie kribben Fort Filip: Deelrapport 2 – aanvullende scenario's (Exploratory study groynes Fort Filip: Partial report 2 - additional scenarios). Version 5.0. WL Reports, 15_042. Hydraulic Engineering Laboratory: Antwerp, Belgium

Progress from the air

DVW - POA

Img. 12 General progress, October 2019.

Img. 13 General progress, January 2020.

Img. 14 General progress, October 2019.

Img. 15 General progress, November 2019.

Img. 16 General progress, May 2020.

Img. 17 General progress, September 2020.

Img. 18 General progress, November 2020.

Img. 19 General progress, March 2021.

Img. 20 General progress, June 2021.

Img. 21 Detailed progress, June 2021.
Img. 22 Detailed progress, August 2021.
Img. 23 General progress, September 2021.

Img. 24 General progress, September 2021.

Img. 25 General progress, November 2021.

Img. 26 General progress, November 2021.

D

Design

Soil remediation project

ABO

The results of the environmental health survey indicated that the formulation of a soil remediation project was a necessary and logical further step to address the soil contamination present. A soil remediation project is an official document whose main purpose is the selection and design of an appropriate remediation approach. The main content components of a soil remediation project are: summary of the relevant boundary conditions, proposal of some feasible remediation techniques and selection of the most appropriate technique and a detailed elaboration of that selected remediation approach.

In addition, a soil remediation project is also an environmental permit application and thus the report should contain the necessary information for the benefit of the permitting authorities.

Selection of soil remediation variant(s)

Within the framework of the BATNEEC principle of the Flemish Soil Decree, a weighted choice must be made between soil remediation alternatives. BATNEEC stands for Best Available Technology Not Entailing Excessive Costs. Freely translated: the best possible technology that is financially feasible. In order to achieve a correct BATNEEC consideration, the judicious selection of soil remediation alternatives is at least as important as correctly performing the consideration process. The most relevant soil remediation techniques were therefore indicated to treat the soil contamination based on case-specific boundary conditions and assumptions. Based on those indicated techniques, several soil remediation variants were prepared.

It is impossible to set out, in rules, which soil remediation variants should be retained for further consideration in the multi-criteria analysis. After all, this depends on preconditions that are different for each case. It is therefore the task of each soil remediation expert to make a selection based on his expertise and to provide justification for why those soil remediation variants are the most relevant for elaboration. In the text below, as part of the soil remediation project, ABO nv considers the different soil remediation techniques and their suitability for the remediation of Fort Sint-Filips. The first list deals specifically with contamination zone 1 or all the contamination in soil and groundwater around the fort structure. The second list focuses on contamination zone 2: the contamination in and under the sediment in the buffer basin.

1: Possible remediation techniques remediation zone 1 - Fort

Technique: Excavation; Contaminated soil is excavated and treated. In order to allow excavation under the groundwater table, dewatering must be performed. This technique is mainly cost-effective for dealing with heavily contaminated source zones.

Applicable: An excavation of the entire core zone is technically feasible. The technique is expensive but has a high degree of certainty and the cost can be determined quite accurately.

Technique: BLE/SVE (soil vapour extraction); In soil vapour extraction, filters are placed in the unsaturated zone and soil vapour is extracted and purified at ground level. In this way, volatile pollutants can be removed from the unsaturated zone and at the level of the groundwater table. When BLE/SVE is combined with groundwater lowering, volatile compounds in the saturated zone can also be addressed.

Not applicable; Given that the contamination consists partly of non-volatile components, BLE/SVE is not a suitable technique.

Technique: PLI (compressed air injection); Compressed air injection involves the introduction of compressed air on filters into the subsurface, normally in the saturated zone. This strips volatile contamination from the soil/groundwater. PLI is almost always combined with BLE/SVE for the final removal of volatilised pollutants. Sometimes PLI is performed at a low flow rate and without BLE/SVE, in which case its purpose is to promote biodegradation by oxygen administration. This then effectively involves a variant of stimulated natural degradation (see below);

Not applicable; Given that the contamination consists partly of non-volatile components, BLE/SVE is not a suitable technique.

Technique: MFE (Multi-phase extraction); Multi-phase extraction is a combination of groundwater extraction and soil air extraction. It consists of a system with extraction filters located at the level of the water table. Both soil vapour and groundwater (and often pure product) are extracted. At ground level, the different flows are separated and remediated separately.
Not applicable; MFE is suitable for the removal of volatile and/or mobile pollutants at the level of the groundwater table. Given that the contamination consists partly of non-volatile components, MFE is not a suitable technique. Also, the extensive vertical profile of the contamination makes MFE an unsuitable technique.

Technique: Stimulated biodegradation; Many pollutants can be biodegraded in the subsurface by naturally occurring microorganisms. This degradation occurs for most pollutants through aerobic processes, but there are some pollutants that degrade better, or exclusively, under anaerobic conditions. Stimulated biodegradation consists of applying products/substances to the subsurface that promote conditions for biodegradation. In the case of aerobic degradation, this usually includes the introduction of oxygen (by oxygen releasing products or compressed air). In the case of anaerobic degradation, this usually includes the introduction of a carbon source. In addition, substances for pH optimisation or nutrients are sometimes administered.
Not applicable; The contamination consists of a cocktail of pollutants. Given that some of these pollutants can only be degraded aerobically and others only anaerobically, stimulating biodegradation cannot be retained as a suitable technique. Also, some of the pollutants concerned are not particularly biodegradable.

Technique: ISCO (In situ chemical oxidation); Many pollutants can be broken down into harmless end products by oxidation. For this purpose, strong, reactive oxidants are introduced into the soil. The quantity of oxidants to be administered depends on the total amount of reduced components in the soil, not just the pollutants present. This makes ISCO more suitable for core zones rather than plume zones.
Not Applicable: An excavation of the entire core zone is technically feasible. The technique is expensive but has a high degree of certainty and the cost can be determined quite accurately.

Technique: ISCR (in situ chemical reduction); Some components can be degraded or stabilised by means of chemical reduction. The implementation is similar to chemical oxidation.
Not applicable; Most of the pollutants present cannot be degraded or stabilised via ISCR. Therefore, this technique is not considered.

Technique: In-situ isolation; In in-situ isolation, the contaminant is sealed off from the environment. This involves blocking the exposure pathways to the various receptors. In most cases, isolation consists of the installation of impermeable seals: horizontal top seals, horizontal bottom seals, and vertical seals.
Applicable: The isolation of the entire core zone is technically feasible. The technique is expensive but has a high degree of certainty and the cost can be determined quite accurately.

Technique: Pump and Treat; Pump and treat addresses the contaminated saturated zone by pumping up the contaminated groundwater and treating it at ground level. All pollutants adsorb to the soil particles to a greater or lesser extent, requiring multiple flushing of the soil to address the contamination. The more mobile the pollutant, the more applicable pump and treat will be.
Not applicable; Given the very high pollutant load and the presence of pure product and few mobile pollutants, pump and treat will take a very long time and be highly uncertain. The cost will be extremely difficult to estimate. Therefore, pump and treat is not considered as a remediation technique.

Technique: Covering with clean soils; For the covering with clean soils, an uncontaminated layer is applied that ensures that direct contact is no longer possible between the contaminated soil and possible receptors (people, ecosystem). This does not always remove all risks, but it usually removes the most critical ones.
Applicable: The isolation of the entire core zone is technically feasible. The technique is expensive but has a high degree of certainty and the cost can be determined quite accurately.

Summary remediation zone 1
Based on the above considerations, the following remediation variants were proposed for the core surrounding the fort:

- **v1** excavation of the core of the contamination;
- **v2** (civil engineering) Isolation of the contamination; by installing impermeable vertical seals around the entire core and an impermeable top seal; the Boom Clay is utilised as a horizontal bottom seal;
- **v3** (civil engineering) isolation of the contamination, combined with excavation of the shallow pure product zones;
- **v4** covering with clean soils and removal of the shallow pure product zones.

2. Possible remediation techniques remediation zone 2 - Sediment
Technique: Excavation; Contaminated sediment is excavated and treated. In order to allow excavation, dewatering must be performed. Given the high proportion of fine grains in the silt and given its high moisture content, cleaning will often be much more expensive or technically infeasible, compared to soil. As a result, excavated, contaminated sediment is often dumped. Before it can go to a landfill site, the silt must be dewatered. **Applicable.**

Technique: Stimulated biodegradation; Many pollutants can be biodegraded in the subsurface by naturally occurring microorganisms. This degradation occurs for most pollutants through aerobic processes, but there are some pollutants that degrade better, or exclusively, under anaerobic conditions. Stimulated biodegradation consists of applying products/substances to the subsurface that promote conditions for biodegradation. In the case of aerobic degradation, this usually includes the introduction of oxygen (by oxygen releasing products or compressed air). In the case of anaerobic degradation, this usually includes the introduction of a carbon source. In addition, substances for pH optimisation are sometimes administered. **Not applicable.**

Technique: Monitor natural attenuation; In certain situations, the biodegradation described above is naturally occurring at a sufficient rate that no additional stimulation is necessary to address the contamination. **Not applicable.**

Technique: (In-situ) capping; In-situ capping (covering) is a remediation technique in which the contaminated underwater soil remains present but (a significant part of) its negative effects on the environment are 'isolated'. In this case, it is a risk-based approach. In this process, the cover material can be either soil or another material that is usually applied layer by layer to the contaminated sediment. **Applicable.**

Technique: ISCO; Many pollutants can be broken down into harmless end products by oxidation. For this purpose, strong, reactive oxidants are introduced into the sediment. The quantity of oxidants to be administered depends on the total amount of reduced components in the sediment, not just the pollutants present. **Not applicable.**

Technique: Covering with clean soils; For the covering with clean soils, an uncontaminated layer is applied that ensures that direct contact is no longer possible between the contaminated soil and possible receptors (people, ecosystem). This does not always remove all risks, but it usually removes the most critical ones. **Not applicable.**

Summary remediation zone 2
For the contamination in and under the sediment of the buffer bassin, the following remediation options were retained:

- **V1** excavation of the core of the contamination in the sediment, followed by off-site reuse, treatment (cleaning) and/or landfill;
- **V2** excavation of the core of the contamination in the sediment, followed by on-site dewatering and on-site disposal of the released silt;
- **V3** in-situ capping of the sediment.

Consideration of most suitable remediation variant - multi-criteria analysis

After selecting the soil remediation alternatives, the BATNEEC consideration is applied through a multi-criteria analysis or MCA. The multi-criteria analysis for the BATNEEC evaluation of soil remediation projects was last updated in 2013 [1]. The modified multi-criteria analysis allows climate change and the sustainable use of resources to be taken into account without losing sight of the goal of remediation. The various criteria weighted in the analysis are divided into four aspect groups:

1. environmental local;
2. environmental regional/global;
3. (implementation) technical and social;
4. financial.

The assessment system aims to compare and evaluate the remediation variants for each aspect group. The methodology of multi-criteria analysis relies heavily on the subjective judgement of the soil remediation professional with respect to the assignment of scores. In order for a particular remediation option to be considered the optimal remediation option with a degree of confidence, the analysis must be conducted with the necessary knowledge and professionalism. The analysis should be as transparent as possible.

In the context of the Fort Sint-Filips soil remediation project, the robustness of the multi-criteria analysis was additionally examined by assigning changes in the weights. This resulted in the selection of a remediation option that is justifiable for parties with a predominantly financial commitment and parties with a predominantly environmental commitment.

Specifically, for *contamination at the fort*, the MCA indicated that alternative 2 (isolation) scored the highest. However, the difference in score with

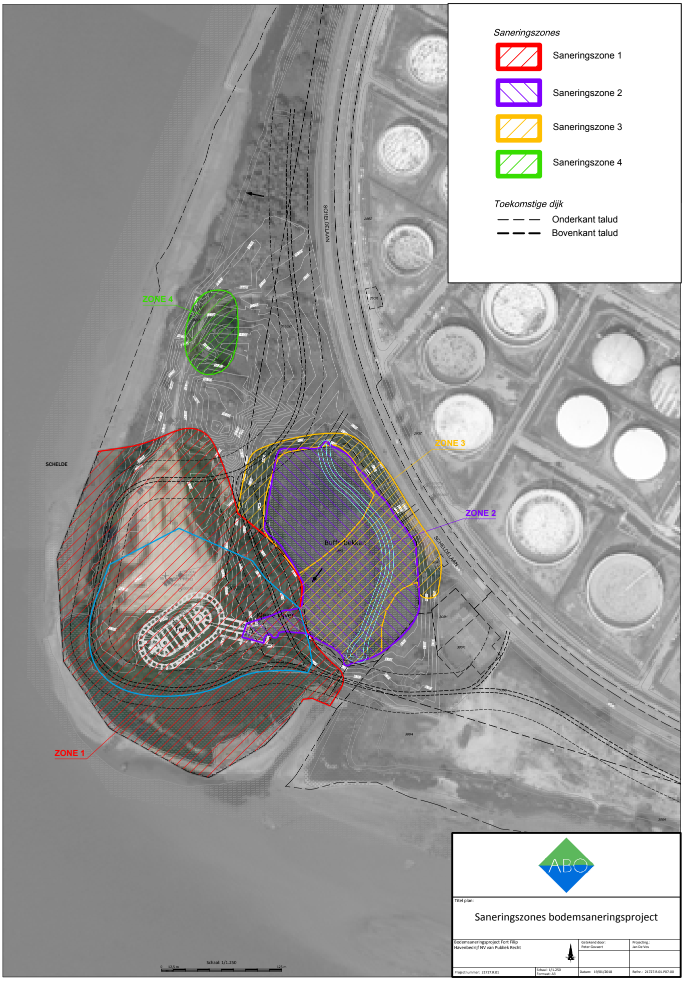


Fig. 03 Designation of remediation zones.

variant 3 (isolation + excavation purely product zones) was rather limited. An additional evaluation was conducted comparing only these two best scoring variants. This confirmed the choice of variant 2. Furthermore, in two additional simulations, in which the weights for the environmental or financial elements were increased, variant 2 (insulation) emerged each time as the most appropriate variant.

For the contamination in the sediment in the buffer pond, the initial MCA indicated that variant 2 (excavation and on-site disposal) and variant 3 (in-situ capping) are almost equivalent: variant 3 scores less than 1% better than variant 2. A comparison between only these two variants shows that variant 3 scores significantly higher and is therefore the most appropriate.

No separate MCA was completed for contamination zones 3 (contamination around the pond) and 4 (northern BTEXN core).

Core 3 was so limited in size and concentrations that the remediation was best tailored to the selected variant for core 2. Since capping was chosen for the contamination in the buffer basin, it was an obvious choice to tackle core 3 by means of covering with clean soils.

Core 4 was located in an area that required excavation independent of the remediation. Hence, full excavation was selected as the only logical remediation option.

Elaboration of remediation approach

Pollution zone 1 - Fort

As described above, the most appropriate remediation technique for the contamination around the fort is isolation. In outline, the following concept was developed:

- an impermeable layer beneath the contamination is necessary so that it cannot spread vertically. It is already naturally present here - Boom clay around -20 mTAW / 30 m below ground level;
- impermeable walls around the contamination is necessary so that it cannot spread horizontally. This is accomplished by the installation of cement-bentonite walls 60 cm thick, installed to at least 1 m in the Boom clay. A thick HDPE (High Density Polyethylene) liner is inserted into the wall to provide additional impermeability and chemical resistance;
- an impermeable top cover is necessary. Rather than serving to prevent direct spread, this is necessary because seeping rainwater would otherwise cause steadily rising water level within the insulation. The top cover should consist of:
  - gas drainage, to prevent volatilised contamination or

decomposition gas from the existing peat layer from accumulating below the impermeable layer;
- HDPE liner: impermeable barrier;
- geosynthetic clay liners: impermeable barrier;
- water drainage, to drain rainwater to outside the insulation;
- living layer of clean soil;
- adapted vegetation that allows management and prevents deep-rooted plants.

Pollution zone 2 - Buffer basin
As described above, the most appropriate remediation technique for the contamination around the fort is in-situ capping. The main risk this eliminates is dispersion towards surface water. After all, the basin is in direct contact with the Scheldt. The capping is constructed by applying an HDPE liner, geosynthetic clay liners and clay layer on top of the existing silt in the pond. This then forms an impermeable barrier that prevents exchange between the contaminated silt and the water in the basin.

In addition, the gully that has naturally formed in the basin will be excavated and concreted to direct water transport past this location and reduce erosion in the rest of the basin.

Pollution zone 3 - Limited topsoil contamination around buffer basin
A re-profiling of the embankments towards the buffer basin had already been foreseen, irrespective of the remediation. This presented an opportunity to carry out remediation of the bank contamination around the basin by means of habitat remediation.
By applying a limited top layer of uncontaminated soil, contaminants with PAH and heavy metals no longer occur at the surface and contact is no longer possible. This removes the risks posed by this contamination.

Pollution zone 4 - BTEXN contamination north of fort
Given that this part of the site had to be excavated as part of the dike works already planned, a complete excavation of the contamination was the only realistic remediation approach.

The contaminated soil had to be selectively excavated, which means that, under the supervision of ABO nv as a recognised soil remediation expert, all contaminated soil is removed and treated. The uncontaminated soil released in this process was stored separately for reuse (preferably on the site itself).

Permit application
A soil remediation project is also an official permit application for an environmental permit that authorises both the project's urban design and

environmental interventions. OVAM (Public Waste Agency of Flanders) is the licensing authority and the declaration of conformity it issues counts as an environmental permit.

OVAM consults advisory bodies to review the soil remediation project. Depending on the context, additional data may be required in addition to the remediation provisions to enable the permit. For example, a water test must always be carried out and the planned discharges must be described in terms of both quality and quantity. Specifically for the Fort Sint-Filips project, an appropriate assessment was also required to identify the impact on Natura 2000 sites. In addition, an archaeology document was also prepared.

1 A reworked version is currently being prepared by OVAM and will soon replace the MCA in force at the end of the drafting of the Fort-Filip soil remediation project.

Technical Design

SWECO

After the preparation and publication of the tender document 16EI/13/58 and a sketch design by De Vlaamse Waterweg nv (then W&Z), the tender for the technical design was initiated on December 2, 2013. Sweco was appointed to prepare the technical design.

The assignment included the preparation of a realistic and supported preliminary design that could serve as a basis for the preparation of the environmental permit application, as well as the EIA exemption and a detailed design. In the present section, we abstract from the different phases (preliminary and detailed design) and explain only the technical aspects.

Preconditions

The basis of the design is an inventory of the various preconditions such as the soil structure, groundwater levels, hydraulic preconditions such as the tide, environmental and constructional quality of the existing soils, the historical value of the fort and the sketch design of the anticipated de-polderisation.

Within the updated Sigmaplan, the target dike height of 11 m TAW was imposed along the Zeeschelde between the Belgian-Dutch border on the one hand and Oosterweel, of which the project is part, on the other hand (www.oosterweelverbinding.be/het-project). At Fort Sint-Filips, taking into account the presence of the strong contaminants, the goal was to move the river dike a little inland, thus bringing a larger area under the daily influence of the tide. Within the Sigma works, the aim was to keep the clean excavated soils for this de-polderisation zone on site to the maximum extent possible. This took into account the soft restoration of the forts and the replenishment of the area behind the crib. On the basis of the design, further preconditions were also indicated:

- Adjusting the ground dike to a crest height of 11m TAW for the purpose of the Sigma dike is preferred. This cannot always be carried out due to lack of space (e.g. due to the buffer pond or pipeline strip);
- A tow-path should be constructed;
- There must be room for a sufficiently wide pipeline strip with guide value of 21.5 m.

Geotechnical investigation

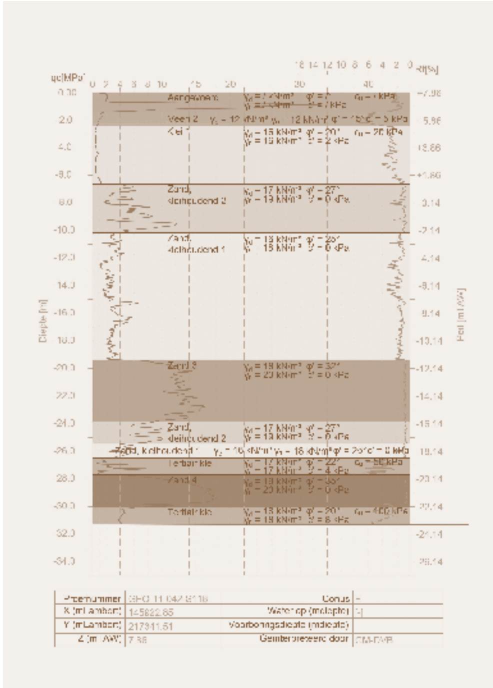
The available soil investigations (borings, soundings and lab tests) were interpreted and translated into a geotechnical subdivision and the assignment of geotechnical parameters to the different layers. The layers are partitioned in accordance with the partitioning assigned in NBN EN 1997-1 ANB-2014 - Table 2.1, supplemented with parameters from NEN 6740,

CUR 166 and the Guideline on Drainage **[Fig. 04]**.

The shear resistance characteristics and compressive modulus are derived from the laboratory study for the low bearing clay layer K1. Unconsolidated, undrained (UU) triaxial tests were conducted by the Geotechnical Department. From this, the undrained shear strength can be determined, which is necessary for the inspection of the modified embankments in the short term, during execution and before completion of the consolidation period after embankment.

The soft clay layer K1 occurs almost across the entire project and is identified in 32 samples. The characteristic 95% value on the mean of the undrained shear strength c_u is determined according to the student's-t distribution and is used for failure under large soil volume. For a calculation under small soil volume, we fall back to the 95% value at the minimum of the undrained shear strength. In the formula below, αprobability and n represent the number of samples, $n-1$the number of degrees of freedom, and $S_n$the standard deviation on the mean value of the undrained shear stress.

$$c_{u,gem,95\%} = c_{u,gem} - t_{\alpha,n-1}\frac{S_n}{\sqrt{n}}$$



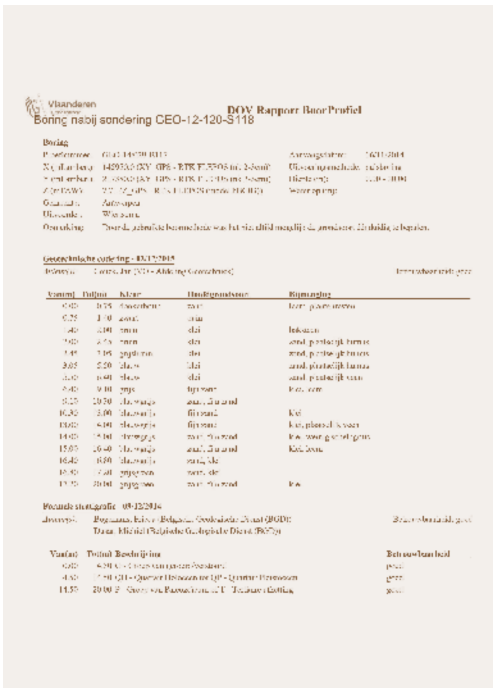


Fig. 04 DOV Report Drilling Profile

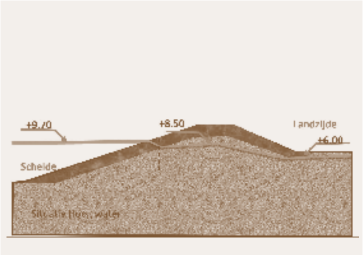


Fig. 05 Hydraulic loading in high water.

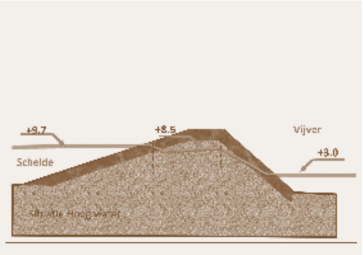


Fig. 06 Hydraulic loading in high water - situation pond.

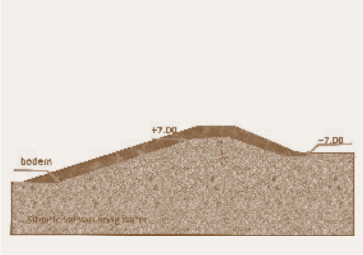


Fig. 07 Hydraulic loading during rapid fall of high water.

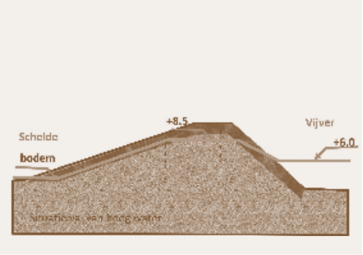


Fig. 08 Hydraulic loading during rapid fall of high water - situation pond.

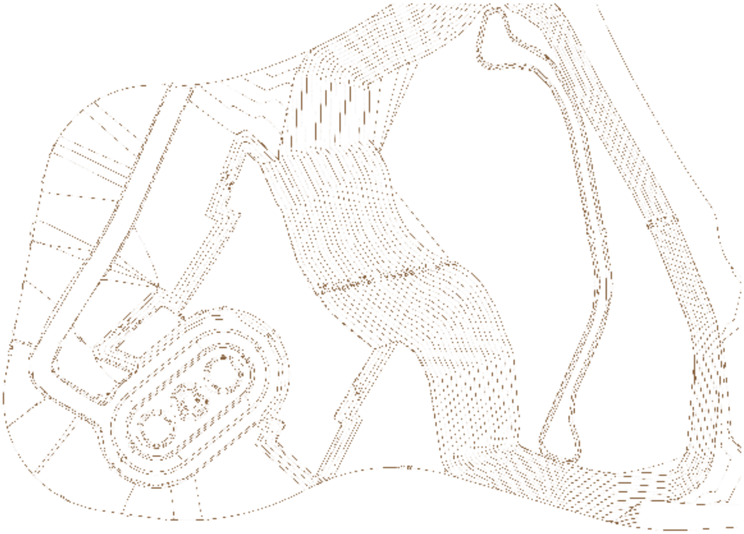


Fig. 09 Contour lines design elevation with landscaping of the fort.

The derived undrained cohesion $c_{u,gem,95\%}$based on the UU triaxial tests for the weak clay layer K1 is 34 kPa, while the $c_{u,min,95\%}$- value is only 16 kPa, the value that is manageable for a shear of a small soil volume. The standard value of 20 kPa, adopted from NBN EN 1997-1 ANB-2014 - Table 2.1, is retained for performing the calculations. In case of insufficient safety, a sensitivity analysis is prepared, determining both failure under the assumption of the standard value and the calculated value.

Measuring cuts

Based on the available soil investigation, the plans from the sketch design and available preconditions such as the necessary embankment as a result of the soil remediation project, some normative cross-sections are selected. The ground level within the contours of the fort is raised to 13 m TAW, whereas in the existing condition it reaches only 10 m TAW in some parts, for example at the level of the embankment on the side of the pond **[Fig. 09]**.

For the project, six type cuts or cross-sections are maintained, both for the inspection of the land slope and the river slope. Some hydraulic loading schemes are considered for each cut **[Fig. 05-08]**.

Design criteria

Design of dikes

The design is tailored to the geometric requirements, constraints and implantation of the dikes in the sketch plan on the one hand and, on the other hand, to technical feasibility.

By technical feasibility, we mean the geotechnical calculations and stability checks of the water barrier. A check of the settlements is necessary to determine the deformation behaviour and the crest height of the levees. This crest height must be guaranteed even after the project is completed.

The sketch design of the levees is then reviewed and adjusted as necessary. The review includes the verification of macro-stability, uplift and bursting under a hydraulic load, sand entrained wells (piping) and horizontal deformations.

The dike revetment is sized and selected according to the wave load: the impact, run-up and attack (direction) of waves. The wave parameters are derived from the study "Study for the construction of flood areas and nature reserves as part of the Sigmaplan - Hydraulic preconditions for testing and designing for safety" prepared by the Hydraulic Laboratory, published in March 2009 and part of the tender document.

Design of hard water barrier

The hard water barrier is subjected to wave loading at storm surge. Under the engaging load, the wall must resist slippage and overturning, and the equilibrium load-bearing capacity must be satisfactory. Underflow of the wall is avoided by installation of a seepage screen. The strength of the wall is tested against NBN EN 1992. Where the wall is located near the future pipeline strip, there is a review of the stability of the wall or whether a sheet piling is necessary to ensure stability.

Design

Settlements

To provide adequate crest height, the existing ground level will be raised over much of the project. The settlements resulting from the embankment are calculated on the one hand using a settlement calculation according to Terzaghi, on the other hand using the Koppejan method. The calculation according to Terzaghi does not allow us to calculate the settlements in time and serves merely to verify the calculated settlements according to Koppejan's method, which do calculate in time.

Settlement calculation according to Terzaghi's formula

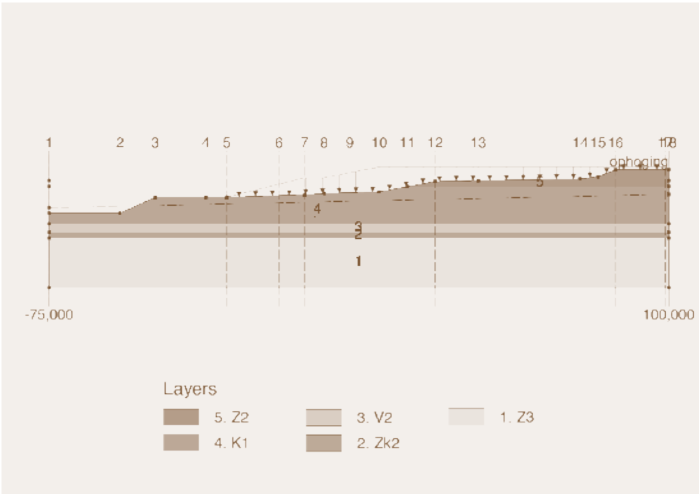
The settlement under a stress increase Δp at the ground level, due to a raising of the existing dike, is the sum of the settlement of each individual layer, calculated using the following formula:

$$\Delta h = \frac{h}{C} \ln \frac{\sigma'_{v;0} + \Delta\sigma'_{v}}{\sigma'_{v;0}}$$

The calculation is performed according to the classical stress distribution according to Boussinesq, with $\Delta\sigma'_{v,0}$ equal to $i \cdot \Delta p$ where i is the influence coefficient according to Boussinesq. The initial effective grain stress is $\sigma'_{v;0}$ calculated halfway through the considered soil layer. For each cross-section, the most representative soil layer structure is selected and a further partitioning is made according to the interval of the report ed probe values, i.e. every 0.20 m. Each layer is subsequently assigned a compressibility modulus according to Sanglerat's formula.

$$C = \alpha \cdot \frac{q_c}{\sigma'_{v;0}}$$

The coefficient α of compressibility is estimated according to the 2009 Guideline on Drainage, the cone resistance q_c is obtained from the CPT. The compressibility of over-consolidated and tertiary layers is appropriately corrected by application of the recharge constant A, if any.



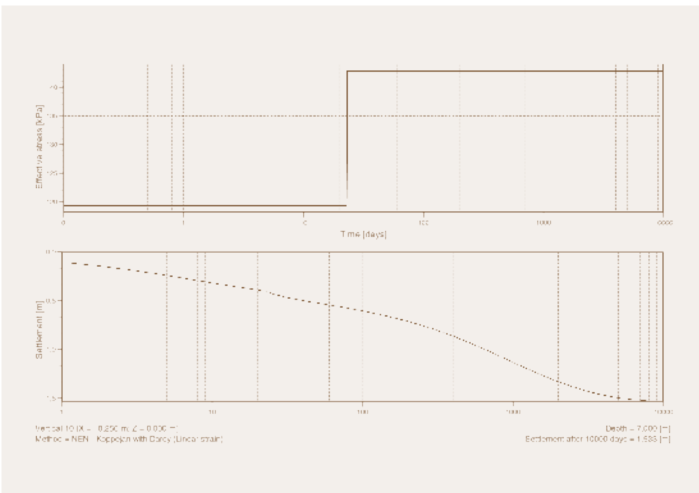


Fig. 10 Graphical representation cut settlement model.
Fig. 11 Imposed load over time and the resulting settlement over time.

Settlement calculation according to Koppejan - D-Settlement

An average water level is used for the settlement calculation. A "pre-overburden pressure" (POP), the difference between the effective stress and the $\sigma'_{v;0}$boundary stress σ_p' (the stress level at which virgin compression behaviour is invoked when exceeded), of 10 kPa is factored into account for historical fluctuations in groundwater levels and associated settlements. The consolidation of the soft clay and peat layers is calculated using Darcy's theory. Permeabilities k_h and k_v have been estimated based on literature.

The calculations - performed with D-Settlement, a software package from Deltares - allow us to calculate settlements in a 2D cut. Typically, 3 phases are factored in. Starting from the initial condition, the necessary embankment and excavation is plotted as a second phase. The third phase is automatically created by the programme and provides an addition to restore the new condition after settlements. The time at which this recovery is performed is pre-set in the software **[Fig. 10]**.

As an example, the settlements are shown at the level of the cut with maximum expected settlements. As a result of the planned embankment, approximately 1.53 m of settlement is to be expected, and this within the existing soil structure. Settlements within the backfill material are not calculated given that proper compaction on site is assumed, as per the rules in Standard Specification 260, along with a compilation of common provisions regarding the study, and execution of works in hydraulic and civil engineering structures. In the calculation, it was assumed that after two weeks, the backfill would be restored according to the designed profile. In reality, the state of the complement changes constantly, with different complements over time. Final site restoration is not anticipated until just prior to the installation of the towing path, i.e. at the end of the project **[Fig. 11]**.

Monitoring settlements during the works

During the work, depending on project progress, the settlements are monitored and compared with the theoretical predictions in order to support decisions such as the scheduling of the asphalt paving behind the Sigma dike. Topographical surveys of the site were made periodically by the contractor. These provide an insight into the evolution of settlements and allow verification of theoretical settlements.

The settlements that occurred at the level of the above theoretically approximate cut are cited as an example. Over a period of more than a year and a half, the ground level was raised up to twice, with the first increase in late 2019/early 2020. The settlement is estimated to be approximately 0.82 m, an underestimate due to the lack of a topographic survey in early 2020, just after the backfill. This result is in line with the previously calculated settlement course where a settlement of 0.95 m can be expected over approximately 600 days. An additional embankment is provided to compensate for long-term settlements. This involves finishing the crest height at the end of the project up to 35 cm higher than the designed height.

Bank stability
An embankment with the following geometric boundary conditions is proposed as the basic design/typical profile:

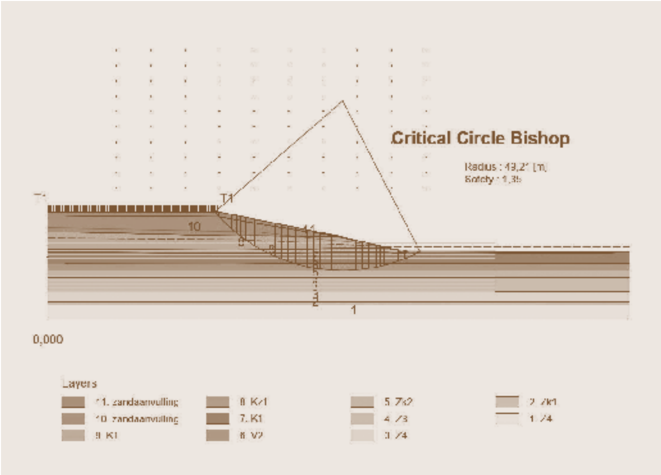
- crest height (after settlement) +11 m TAW = Sigma dike;
- crest width 5.50 m;
- slope of land bank 12/4;
- slope of riverbank 16/4.

The envisioned detail structure consists of a dike with a core capped with 1 m of oily soil as a hydraulic barrier with a stone revetment of 0.5 m in thickness on top of this, separated by a filter geotextile. it is good practice to apply the layer of oily soil in a wedge shape, with a wider base in cross-section so that the hydraulic resistance is greatest where the potential is also greatest. On the crest, a traffic load of 15 kN/m^2 is taken into account.

The embankments have been calculated both drained and undrained. An undrained situation occurs with low permeable soils that are additionally loaded by, for example, embankment or drainage (increase of effective stress). Water located within the grain structure, i.e. pore water, cannot dissipate quickly under increasing load, resulting in a temporarily altered soil reaction. This soil reaction is investigated during inspection of the instantaneous or undrained condition. The 'final state' refers to a drained situation.

The normative cuts, characterised by a specific geometry such as a steeper slope, layer structure of the soil and/or deviating crest height, are checked with regard to macro stability, seepage (piping) and floating and bursting.

Checking macro stability in D-Geo Stability
The calculations for the dikes are performed in D-Geo Stability, calculation software released by Deltares. We import the settled soil structure from D-Settlements and calculate the macro-stability according to Bishop. The calculation according to Bishop uses a lamellar calculation method. A hypothetical point is chosen in which a shear line with the shape of a circular segment is drawn. This line delineates a ground mass within which we will write out the balance of forces. Within each slat, the driving and resisting forces are calculated. The driving forces consist of the force exerted by the adjacent slats, the weight of the slat and the reaction force exerted



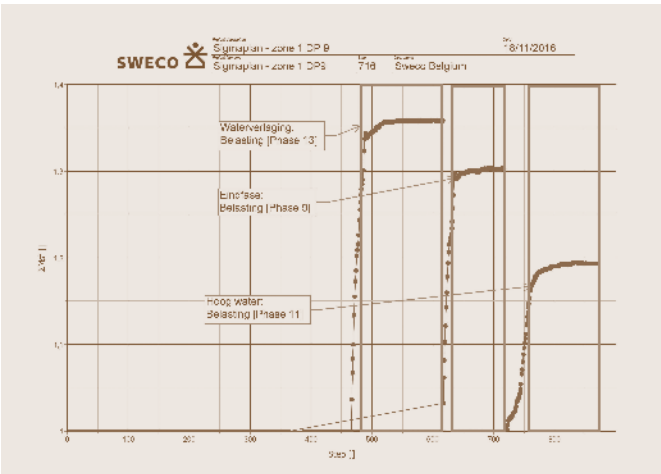


Fig. 12 Graphical representation results model macro-stability.
Fig. 13 Results of review in Plaxis 2D of macro-stability.

perpendicular to the shear line. The resistive force consists of the friction at the shear plane. This friction can be calculated in the instantaneous (undrained) or final (drained) state.

- Undrained: $\tau = c_u$
- Drained: $\tau = c + \sigma'_v \tan(\varphi')$

Figure 12 shows the critical slip plane for an embankment on the pond side of Fort Sint-Filips. The calculation is performed in the serviceability limit state. Gripping loads, volume weights and material properties are not probed. The required safety, the ratio of resisting to driving forces, should be greater than 1.1 in instantaneous (undrained) condition and 1.3 in ultimate (drained) condition. The testing conditions are imposed in Standard Specification 260, a compilation of common provisions for the study and execution of works in hydraulic and civil engineering works.

Additional measures of bank stability

The requested safety of the embankments cannot be guaranteed for each normative cut without additional measures. The geometry of the pond bank is determined by the necessary buffering capacity (volume) of the pond. The pond is connected to the drainage of an adjacent business and during high water the pond should have sufficient capacity to buffer the discharge water. The presence of contaminated soil does not allow the levees to be moved. The slope of the embankment on the pond side is a result of the interaction between the preconditions regarding the surface area nature to be achieved and the buffer capacity to be retained in the pond.

To stabilise the slope, vertical nailing with piles is provided as shown in Figure 14. The nailing is calculated using a finite element calculation, this is because the method allows the soil-pile interaction to be properly modelled.

Checking macro-stability in Plaxis

The bank stabilisation by nailing is controlled in a finite element software package. Plaxis 2D, calculation software released by Bentley, is used to check the macro-stability and estimate the internal force effects in the piles **[Fig. 13]**.

The testing conditions for a "method of optimized sliding surfaces" described in the standard tender document (HST 21 §6.4.11), are limited to a required safety factor of 1.25 in ultimate (drained) condition, 1.1 in instantaneous (undrained) condition.

Review of sand entrained wells (piping) with Bligh and Lane

Sand entrained wells can occur when there is an imbalance of hydraulic conditions to the left and right of a water retaining structure. Due to the

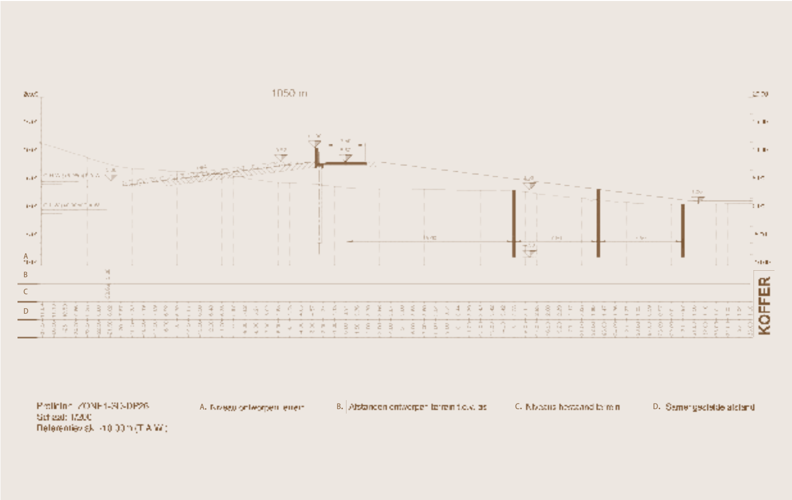


Fig. 14 Cross-section of vertical nailing.

large pressure difference, water makes its way through a permeable soil layer just below the water retaining structure. Ground particles are lost during transport, allowing water to make its way even faster from the side with a high water level to that with a low one. The result is reduced slope stability (micro-stability) on the side with low water levels. The reduction occurs due to the loading of the soil particles under a flow. If the hydraulic condition persists for a long time, the dike may fail in its entirety; this is referred to as dike failure.

A piling sheet is therefore provided under each water retaining structure within the project. By adding a contiguous screen consisting of piling sheets, a hydraulic barrier is formed and the bypass length or mitigation path is extended to prevent sand entrainment (seepage or piping). This type of hydraulic barrier is also called a 'seepage screen'. The seepage screen is created up to a low permeable soil layer such as a clay layer or peat layer. Generally, such layer is usually cut at about 2 m ground level. It was decided to provide a piling sheet under the water barrier over the entire project; by implementing a piling sheet in limited length, the mechanism is completely excluded.

Where the retaining wall is adjacent to the pipeline strip managed by Port of Antwerp, a piling sheet and anchor will be implemented. In addition to acting as a seepage screen, this screen was initially envisioned to allow for excavation when constructing new pipelines.

The testing conditions are defined in the standard tender document (HST 21 §6.4.11) and depend on the calculation method applied. When checked according to Bligh and Lane, a safety factor of 1.0 is required.

Check floating / bursting

When designing a dike built on a low permeable soil package of limited thickness, with the presence of a water-bearing sand package below that is connected to the side where there is a high water level, there is a risk that under the increased water pressure in the sand package, the low permeable soil layer will burst where the thickness is minimal, often just behind the dike.

No such situation arises in the project. The testing conditions are defined in the standard tender document (HST 21 §6.4.11). A safety factor of 1.2 is required.

Stability of crushed stone

Under wave loading, crushed stone can be carried away with the current. The dimensions of the crushed stone are determined using the 'van der Meer' rules. The stone must withstand the onslaught of currents, wind waves and ship waves. A minimum diameter D_n of 0.46 m must be applied. Specifically, there is a need for stone filling in the 60/300 kg grading. A layer thickness of 0.75 m to 0.8 m is maintained.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Financing & Procedures

Collaboration

DVW - POA

Since Port of Antwerp wanted to expand the pipeline capacity between the Scheldelaan and the Zeeschelde, and De Vlaamse Waterweg nv had planned the realisation of the Sigmaplan in that same limited period, a collaboration was the natural course of action. An initial cooperation agreement in principle was drawn up by the responsible project managers/engineers at both organisations. Approval by the Board of Directors of the then W&Z and Port of Antwerp followed on February 12, 2014. The cooperation agreement included the various interests and principles that guided both organisations in elaborating the projects. A total of four zones were defined in which certain bottlenecks were identified and specific solutions proposed:

Zone 1 (1,894 m): the zone around the former Fort Sint-Filips in which tidal nature objectives were set by the Flemish Government and in which a crucial pollution problem from historical incineration activities had to be solved. In addition, there is also a drainage problem from adjacent businesses in this zone;

Zone 2 (941 m): a zone consisting of a narrow strip between existing tidal nature and the Scheldelaan where a dike and pipeline strip already overlapped, even before a planned raising of 2.5 m of the flood barrier;

Zone 3 (1,668 m): a zone around the Van Cauwelaert and Baudouin locks where the outer harbours, pipelines and companies were built up to near the banks of the Scheldt;

Zone 4 (2,568 m): a wider zone where the lowest points in the water barrier were located. Additional tidal nature could still have a place here.

In total, an area of more than 7 kilometres is involved in which existing bottlenecks for the doubling of the pipeline capacity will be eliminated and in which the water barrier will be constructed up to 11 m TAW to protect the port infrastructure against storms with a return period of 1 in 10,000 (level as of year 2000) from the Scheldt. Realisation agreements are concluded for the various zones; these include practical arrangements regarding issues such as financing.

For Zone 1, about which we will go into more detail here, this agreement was concluded on August 22, 2017. This was the starting signal for Port of Antwerp and its remediation expert ABO nv and De Vlaamse Waterweg nv and its designer Sweco to join forces with regard to this particularly challenging zone.

Interreg Smartsediment

DVW

Smartsediment is a collaboration established in 2016 between the Dutch Province of Zeeland, Rijkswaterstaat Zee en Delta, the Royal Netherlands Institute for Sea Research (NIOZ), the Vereniging Natuurmonumenten and the Flemish parties Afdeling Maritieme Toegang of the Flemish Government and De Vlaamse Waterweg nv. The collaboration aims to restore the balance between biodiversity, soil and other functions in the Scheldt Delta through the use of Smartsediment. Out of a total budget of 7,582,687.68 euros, Interreg contributes 3,791,343.84 euros or 50%. Several subprojects fall under the Smartsediment project:

- replenishment and monitoring of Roggenplaat;
- construction of a crib at Fort Sint-Filips;
- development of an ecosystem service tool;
- ecological monitoring of the Trial Disposal Suikerplaat;
- monitoring of the Lower-Scheldt disposal sites (Parelputten and Ketelputten).

In addition to funding the projects, Interreg's approach has contributed greatly to the communication and collaboration around the projects and the portrayal of the challenges that are being addressed in the process.

ref. https://www.grensregio.eu/projecten/smartsediment; https://youtu.be/Tp7SU5HUkgY

Cooperation users of the buffer pond

POA

Based on the survey data by accredited soil remediation experts commissioned by Port of Antwerp of the entire Fort Sint-Filips site including the pond/buffer basin, the buffer basin used as a buffer for the treated company wastewater and water from the Scheldelaan was also found to contain contamination that needed to be remediated.

The soil surveys conducted showed that the contamination of the sediment in the basin was mainly caused by dispersion of the contaminants (mineral oil, PCBs, VOCs) also found in the fort. But in addition, a clear gradient in concentrations was observed that decreases with distance from the location where there is a connection between the basin and the fort. It was broadly clear that the disposal of waste water had also contributed to mineral oil contamination for decades. Based on the occurrence of mineral oil contamination in (quasi) absence of parameters unrelated to the activities of the basin user, an estimate of the possible maximum contribution of the discharge was made.

The necessary practical and financial agreements were made (and recorded) with the parties concerned regarding the approach to this contamination. Further discussions led to a combined execution of the works. The necessary agreements were also made regarding the follow-up of the work on the drainage construction and the buffer basin during execution.

Permits

DVW - SWECO

In order to ensure that the project in Fort Sint-Filips is functionally and geographically coherent with the other zones in which the Sigma plan has not yet been implemented in the port area on the right bank of the Scheldt, it was decided to incorporate the four zones into a single permit application, which sought to achieve a phased implementation. A separate permit process was followed in connection with the planned soil remediation works (see the section entitled Soil Remediation).

The phased approach in the case of the Sigma works was laid down in more specific terms following advance consultations with the Environmental Impact Assessment Department, the Agency for Nature and Forests and the Permits Department, all three of which form part of the Government of Flanders. An initial procedure was followed in order to obtain an exemption from the need to submit an Environmental Impact Assessment (EIA) for the project. The purpose of that exemption was to demonstrate that the planned interventions were not expected to result in any significant, negative effects. A second procedure was required in order to obtain planning permission. For that purpose, the zone in which the remediation work was going to be carried out had to be omitted from this permit application, in view of the fact that a separate procedure had been followed in that regard (see above).

This made it possible to avoid any issues concerning conflicting stipulations in the two permits, given that the soil remediation project had not yet been completed at the time the application was made. Both procedures were completed smoothly, despite the fact that additional consultation with the Agency for Nature and Forests was needed in order to be certain that the stipulated conditions would be fulfilled. The application for exemption was submitted on 23 February 2015. Exemption was obtained on 26 October 2015. The permit application was submitted on 31 May 2016 and almost one year later, on 21 April 2017, the permit was obtained.

Tendering

DVW

The tendering of the works, following the preparation and publication of the tender document AZZ-18-0011 and the associated technical plans, was undertaken for the first time on November 19, 2018. Given the complexity and interrelatedness of the various components in the tender document, after requesting additional justification from the bidders, it was decided not to award the contract on March 22, 2019 and to include the necessary additional clarifications in the tender document. An information meeting for potential bidders was also organised before the opening of the bids so that any additional questions could be answered.

A second tender (opening of bids) took place on May 13, 2019. The specification AZZ-19-0015 included five sections, which are legally interpreted as five independent contracts. This made it possible to clearly distinguish the payment modalities between Port of Antwerp and De Vlaamse Waterweg nv as well as the European co-financing (Interreg) in this:

- fixed part 1: Sigma Works South (DVW);
- fixed part 2: remediation works Fort Sint-Filips and buffer pond (POA);
- fixed part 3: construction of crib (Interreg);
- conditional section 1: earth retention and pipeline strip (POA);
- conditional section 2: Sigma Works North (DVW).

The tender document included two award criteria, price (at 76/100 points) and plan of action (at 24/100 points). Based on these criteria, tenderer TM Jan De Nul-Envisan-DEME Environmental was found to have the highest score of the five tenderers. The works were awarded to the contractor for a total amount of 19,896,883.25 euros (excluding VAT).

Special techniques in the spotlights

TM

Img. 27 Installing piling sheets in CB wall.

Img. 28 Remediation Zone 4.

Img. 29 Liner works pond.
Img. 30 Fascine mattresses.

Img. 31 Placing crushed stone.
Img. 32 Silt buffer pond.

Img. 33 Placing concrete piles.

Img. 34 Demolition of roof structure.

Img. 35 Concrete works.

F

Implementation

Preparation

TM - DVW - POA

In this book, the execution section provides a unique glimpse into the vision of the contractor (TM Jan De Nul-Envisan-DEME Environmental) and shows the practical challenges that were encountered during the execution of the works. It is not intended to be a manual for future works but rather a reflection of experiences in the field.

The works were carried out in an integrated manner with a temporary partnership (TM) between three different firms: Jan De Nul, Envisan and DEME Environmental. To organise cooperation between the different firms, several committees were formed. This allowed the TM to function as a separate firm with its own structure and clear responsibilities. An executive committee (DC) was therefore elected with decision-making authority for the TM. To support the site management, a technical committee (TC) was also established with an advisory function. The organisational chart for the site management was drawn up so that each firm was adequately represented.

The commencement order for fixed sections 1 (Sigma South) and 2 (Sigma North) was issued on October 14, 2019. However, the practical and administrative preparation of the works had already started in August 2019. In September 2019, three equivalent full-time engineers were employed with a view to starting in mid-October of the same year.

An important aspect of the preparation process was the creation of a robust schedule. It was important from the outset to map and coordinate the various interactions between the remediation work, large-scale

earthworks, civil engineering works, dike works and the volume balance in general. The challenge was mainly the interferences between the different types of works and the incorporation of the overall volume balance.
Because so many different types of work were involved, such as the remediation of a nineteenth-century fort, the covering of a pond that is not accessible and the construction of a groyne dike in the Scheldt, the techniques, work methods and equipment to be used were not fully known in detail at the start. This was only the case as more insights were gained into the works and, in turn, an exact schedule could be drawn up.

For volume balance and earth movement, it goes without saying that an excavation in one zone must be accompanied by an elevation in another zone in order to work cost-effectively. After all, intermediate storage of soils is an expensive and therefore avoidable intermediate step. The lack of site surveying made it impossible to perform a proper volume balance in advance, and it was also not initially possible to survey the site, either manually or with a drone measurement, because of the dense vegetation around the buffer pond and in the northern part of the site. Thus, the volumes mentioned in the bill of quantities were used as a basis but, again, estimates had to be made since several items contained both volumes in elevation and in excavation (added together). The proportion of elevation or excavation within these items was unknown.

As on any construction site, contracts had to be entered into with subcontractors and suppliers. The main contracts that had to be negotiated in the preparatory phase were those for the supply of crushed stone, the execution of the civil engineering works and the manufacture and installation of fascine mattresses. For works and supplies to be carried out over a period of about 1.5 years, the main focus was on agreements concerning price revisions or price variations. Given the size of the works, the availability of materials and/or equipment was also an important consideration and selection criterion.

Introduction remediation

TM - ABO

A total of four different remediation zones were defined for the entire site.
For completeness, these are again listed below:

Zone 1: the old Fort Sint-Filips and surrounding land, delimited to the south and west by the existing banks of the Scheldt River and to the east by the buffer pond. The northern edge of this zone was delineated by the soil remediation expert ABO nv based on sampling and contamination present; **Zone 2:** the buffer pond. The perimeter of this buffer pond is naturally fixed by the surrounding embankments; **Zone 3:** the northern embankments of the buffer pond. The perimeter of this zone was determined by ABO nv during the study phase; **Zone 4:** a zone north of the fort where contamination was identified in the solid part of the earth. The contours were indicatively established by ABO nv in the study phase using soil samples.

A different remediation technique was developed for each zone in the soil remediation project. It involved landfill encapsulation (zone 1), capping with HDPE liner (zone 2), covering with clean soils (zone 3) and excavation and treatment of the contaminated soils (zone 4). This range of techniques to be applied reflects the complex nature of the works that had to be carried out. These large-scale and in many ways unique remediation efforts had to be combined with the many civil engineering works and large-scale earthworks during execution. The interference will be explained in detail in the following paragraphs.

Zone 1

TM - ABO

Zone 1 is the area of the nineteenth-century Fort Sint-Filips and the immediately surrounding land that had to be encased in a cement-bentonite wall. Initially, this area was estimated at 22,022.7 m2. At the start of the works, additional confining drill samples were taken, further extending the contour line along the northern side. The final size of Zone 1 was 27,183.69 m2.

The remediation concept for Zone 1 was discussed in detail in the soil remediation project and previous sections. From a practical point of view, the works in zone 1 can be listed as follows:

1. preparatory earthmoving to allow the cement-bentonite wall to be installed (laying out ground level and constructing new slopes/dikes of the Scheldt);
2. the installation of the cement-bentonite wall including selective excavation and the installation of HDPE liner and sheet piling in the wall;
3. top cover of the fort zone: clearing the fort and demolishing the roof structure, filling the fort with soil and installing the top cover, consisting of gas drainage, geosynthetic clay liners, HDPE liner, water drainage, a living layer and soil.

1. Preliminary earthmoving

The blue perimeter line shown on figure 3 (page 75), is the centreline of the cement-bentonite wall to be installed. Transforming the existing theoretical contour line into the new one was a challenge in practice.

The embankments of the Scheldt were to the south and west of zone 1. To the east, a small pond was present that had to be included in the encapsulated zone. Along the northern edge, only limited preliminary excavation was required. The final embankments themselves, as well as the cement-bentonite wall, had to be moved up towards the Scheldt and constructed on the separation between the small pond and the large buffer pond. The difference in height between the existing ground level between the two ponds and the final finish level was approximately 7 m.

Because the plan was to begin the installation of the cement-bentonite wall as soon as possible, it was decided to focus first on the construction of the embankments of the Scheldt in this zone. Following this, a dike was constructed between the small and large ponds. Stability was critical here and throughout. Accordingly, the existing CPT soundings were used to characterise the subsurface and there was close consultation with Sweco for the stability study.

For the construction of the embankments of the Scheldt, soft layers on the existing banks had to be removed. These layers were a combination of accretion and the humus-rich layer from the reeds. The soils were sampled by ABO nv and reused if possible. Some of the soils were found to be contaminated with mineral oil and were treated off-site.

Another problem arose near the small pond: the water was polluted, could not be drained and there was silt on which a dike could not be built. The water was therefore pumped and treated using a water treatment plant (WWTP) before being discharged. The silt was pushed up towards the fort so that it could not be trapped under the new embankment.

The deeper (soft) layers were known at the outset because of the extensive CPT soundings but the presence of the upper layers was not initially taken into account to an adequate extent. Therefore, after identifying these upper silt layers and estimating the impact, as well as when identifying the silt in the buffer basin, consultations were made with the internal geotechnical department and feedback was given to the principal and Sweco.

The photos on the adjoining page show the situation during this earth movement in chronological order. Image 36 shows the original ground level after vegetation removal. It shows the small pond (central) and limited embankment that was present with which the ponds were separated. Furthermore, one can also see the masonry structures in the small pond that form the entrance to the fort. The first other earthwork consisting of levelling and embankments can be seen in image 37. Finally, image 38 shows

Img. 36 Fort zone after vegetation removal.
Img. 37 Fort zone after initial levelling.
Img. 38 Fort zone implementation phase.

the situation during the works. The photos clearly show that a substantial dike was constructed. That dike is part of the final soil profile.

2. Installation of the cement-bentonite wall with HDPE liner and piling sheet

There were several challenges faced during this phase:

Inaccessible area in the middle of the (fort) site zone

The central part of Zone 1 is the nineteenth-century fort that was almost entirely underground. From the beginning of the works, this area was cordoned off and off-limits to equipment or personnel. Indeed, the stability of the structure was not known and the risk of collapse was too great. This hindered the works in the sense that the middle part of zone 1 was not accessible and work had to be carried out around it. This caused the necessary logistical adjustments for both transport within this zone and for the laying of pipes. Image 36 shows the outline of the fort from the orange site nets.

The presence of the inaccessible zone of the fort and the basins meant that there was only one track around Zone 1 for site traffic and the installation of the piping for the cement-bentonite mixture. It was important to coordinate all the works properly because there was only one site road available and that same site road was also the working track for the cement-bentonite wall crew. A transportation plan was drawn up and the use of this site road had to be taken into account at all times in planning as well.

Protection of personnel in the context of severe contamination

The biggest challenge with regard to contamination was undoubtedly the adequate protection of the personnel involved in the works. The main contamination in the underwater and floating layers, where excavation was required, were vinyl chloride and chloroethanes at extremely high concentrations. These components are volatile and very harmful to health.

Establishing a safe limit for working with VOCs was crucial, but not easy. After all, while there are devices (PIDs) available for the instantaneous measurement of concentrations of VOCs present in the air, they do not indicate which components are being measured. Given that a mixture of potentially hundreds of substances was always measured, each with its own known limit value, determining the limit value of the overall mixture was not a simple task. An external and independent firm was therefore appointed to check which safety measures had to be taken and what could be regarded as a safe limit.

Based on the known data from the soil remediation project, it was calculated which substances would be released and in what proportions. This was tested against reality using some test campaigns for air measurements.

Air measurements were taken on a regular basis during the initial excavation both in the vicinity of the fort zone and in other contaminated areas around the fort, where similar contamination was expected. Although the total concentrations here were many times lower, the goal was still to know the relative concentrations of the most dangerous components. Based on all this data, a safety limit could be determined for the mixture as a whole. The main safety measures that had to be taken were:

- avoid skin contact with the contaminated sludge/soil or ingestion by mouth;
- avoid inhaling the airborne contaminant;
- avoid taking the contamination into the welfare facilities or vehicles.

All employees who could come in contact with the soil or sludge from the trench for making the cement-bentonite wall were required to wear disposable coveralls continuously. At the end of the shift, the coveralls were deposited in special waste containers for chemical waste. They were also required to wear special chemical resistant gloves and safety glasses. It goes without saying that it was also strictly forbidden to eat, drink or smoke on site. Based on these measures, contact with the skin or ingestion by mouth could be avoided.

In order to keep the contamination from being carried into the welfare facilities, cars or homes, a decontamination unit was used. This unit consisted of two units: one clean and one dirty. Before entering the decontamination unit, the footwear could be cleaned with a boot cleaner. In the decontamination unit, one could take off and deposit the disposable coverall, and remove work footwear and all dirty work clothes. Hands could then be washed and clean clothes and footwear put on in the clean unit. It was mandatory to pass this unit and remove all dirty work clothes at the end of each shift. At the beginning of the shift, workers had to enter the decontamination unit through the clean unit in order to put on work clothes.

Near the excavation front, PID meters were also attached to the excavation crane. If the safety limit of measured VOCs was exceeded an alarm went off. Two limits were defined: one for wearing a mouth mask and one for stopping work. The first limit was 50% of the calculated safety margin. When this limit was exceeded, it was mandatory to wear a mouth mask with filters (ABEKP3). It should be mentioned that 100% of the safety limit corresponds to the safe value if one works a full working day at the given mixture each time during a full career. For safety reasons, a mask was already worn at 50% of the limit. The second limit was based on the efficiency of a mouth mask with filter. Above this limit, this type of mask would no longer provide sufficient protection and a mask with compressed air had to be used.

In practice, masks were used almost continuously while digging the trench for the cement-bentonite wall. Each time the excavation bucket came to the surface, there were peaks above the first safety limit but well below the second safety limit. So, ultimately compressed air was not required.

Semi-solid and contaminated sludge

A cement-bentonite wall is installed by excavating a trench with a grapple on a cable crane and then pumping a liquid mixture of cement and bentonite into the trench. To ensure that the grapple always goes into the ground in the same place, concrete guide walls of 1 m are placed in the subsoil along both sides of the route. The mixture keeps the trench open and forms a water-impermeable wall after curing. This process involved digging through both floating and sinking layers. The last meter of the wall was placed in the Boom clay.

ABO nv commissioned the excavation to be performed selectively as far as possible. It was expected that contaminated soils or layers were still present at the level of the wall alignment. A plan was drawn up on which the different qualities were visible, both in depth and in the longitudinal direction. 'Green' (probably not contaminated), 'orange' (possibly contaminated) and 'red' (very probably contaminated) were chosen. The fourth category was 'clay'.

When making a cement-bentonite wall, the excavated soil is always a mixture of the in-situ soil with the cement-bentonite sludge. This mixture is semi-solid and cannot be stockpiled. In order to store and analyse the different categories of excavated soil separately, several basins were dug within Zone 1, which can be seen in image 38. The basins were lined with liner.

Two site trucks with waterproof loading bins were used for internal transport from the excavation area to the basins. The driver was always notified by the excavator operator regarding the bin in which to discharge. To prevent cross-contamination, the basins were used for the same grade (green/orange/red/clay) each time. Two bins were provided per category. This meant it was possible to switch smoothly when one bin for a particular category was full.

The sludge, as mentioned, was semi-solid and could not be easily removed from the site. When the bin was full, the sludge was made semi-solid using classic lagooning techniques. The contaminated soils were removed from the site for off-site treatment.

Installation of HDPE liner at depth

In one section of the wall, HDPE liner had to be installed down to the bed to further reduce water permeability. This was done using rolls of liner that were sunk with a weight to the bottom of the trench. Image 39 shows the cable crane (right) with the drop weight. To prevent the liner from sinking under its own weight into the not-yet-cured mortar, it was suspended from

Img. 39 Insertion of liner.

a kind of trestle. The different rolls of liner had to be attached to each other so that they would form a contiguous whole in the wall. This was done using a Geolock system [Fig. 15].

Potential sinking of piling sheets
In another part of the wall, piling sheets had to be installed for the purpose of stability. The piling sheets could simply be introduced into the uncured mortar with a cable crane. To avoid sinking, these were held up with a steel tube inserted through an eye at the top of the piling sheet, resting on the concrete target walls. The transition from the HDPE liner to the piling sheet was accomplished with a Geolock that was bolted to the first and last piling sheet.

3. Upper deck of the fort
The stability of the fort was unknown before the works began and the masonry structures appeared to be (chemically) degraded. In order to avoid future settlement or subsidence, it was important to ensure a stable working surface before laying the sealing layers. To achieve this, the old fort had to be filled in and stabilised with soil [Img. 40].

The roof was demolished using hydraulic excavators with breakers. The masonry debris was mixed with soil and compacted in the rooms of the fort. The floorboards and walls were retained. In the context of blending, soils were used from zones that needed to be lowered within the CB wall. The backfilled chambers were compacted so that differential settlements could not occur. Ground or rain water was present in some rooms. This water was contaminated by contact with the contamination in the fort zone and needed to be removed. The water was treated by a WWTP before being discharged. During these works, no further excessive VOCs in the air were observed.

The demolition of the roof and the filling of the rooms had to be done systematically and room by room from the outside in. The core of the fort could only be reached by first filling in the outer chambers.

After the fort was filled to a stable state, an impermeable cover had to be constructed to completely encapsulate the contamination in and around the fort. Four layers were provided: (from bottom to top) gas drainage, geosynthetic clay liners, HDPE liner and water drainage.

For the drainage layers, sand was brought in from the site and spread to the maximum extent possible. Several zones had been tested on site in advance and the appropriate sand zones were excavated only when they were needed for the drainage layers. Drainage pipes have been buried in both the gas drainage and the water drainage. The pipes for gas drainage were connected to an HDPE sump with activated carbon for passive removal and purification of any released gases. The water drainage, the top layer that should drain rainwater, drains towards the buffer pond and the Scheldt.

Img. 40 Excavation of the fort.

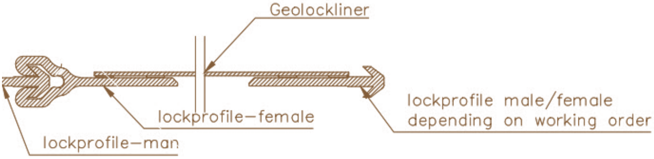
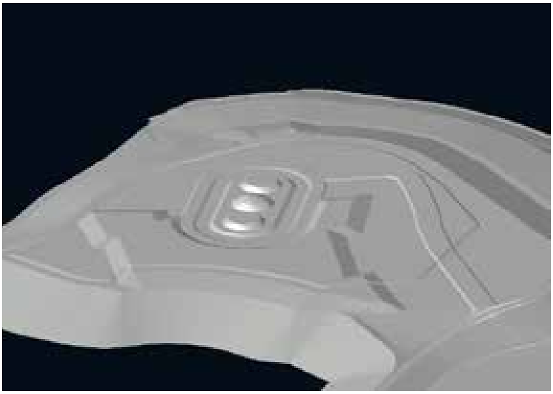


Fig. 15 Geolock system liner.

Img. 41 Cover isolation fort zone.

Fig. 16 Render construction of topsoil.



Geosynthetic clay liners were rolled out on the gas drainage layer with the necessary overlap. To ensure impermeability at the seams, bentonite powder was applied between the mats. Along the edge, the bentonite powder was pre-sprinkled in the factory, on the ends this had to be done manually, on site. On top of the geosynthetic clay liners, HDPE liner rolls were unrolled and welded together. On top of the HDPE liner, the water-draining layer was then constructed. In order to make the location of the drainage layer clear in any future (ground) works, a geotextile was installed before the top cover was created **[Img. 41]**.

The top cover consisted of clean soils, either from the work site or brought in, with a final cover layer of 30 cm in topsoil. The soil was sown with a grass mixture.

In order not to lose the historical value of the site, the ground plan of the nineteenth-century Fort Sint-Filips and the earlier sixteenth-century Spanish fort were reflected in the profiling. Figure 16 shows a simple render from the control models of the machines used to lay the soil.The buffer pond is located at the bottom of this figure. The star shape of the sixteenth-century fort is clearly recognisable therein, as are the three domes of Fort Sint-Filips and a ring moat representing the old courtyard. The outer oval embankment, next to the ring moat, shows the location of the outer chambers of the fort.

Installation of monitoring wells by Geosonda

Beyond the Jan De Nul-Envisan-DEME Environmental TM assignment, monitoring wells had to be installed both inside and outside the cement-bentonite wall. The main purpose of these monitoring wells was to be able to monitor the water levels just inside and outside the fort zone and allow for possible sampling of the groundwater.

Port of Antwerp appointed a contractor, Geosonda, to carry out these works. The TM needed to level and prepare the work zones and adjust the schedule so there were no interference with Geosonda. The monitoring wells were installed simultaneously with the installation of the final soil layers on the water drainage. For Geosonda, it was therefore also important to coordinate the order of drilling at the different locations with the planning of the TM, on the one hand for the works related to covering the fort zone and on the other hand to keep the site roads around the fort clear.

Since the monitoring wells were placed after the impermeable cover was realised, Geosonda had to go through the geosynthetic clay liners and HDPE liner. To avoid uncontrollable damage to the cover, the HDPE liner was dug out and Geosonda penetrated the liner in a controlled manner. Afterwards, the liner was repaired locally and HDPE pipes were placed over the monitoring wells and welded to the liner. The HDPE pipes were extended to the level of the future ground level. The space between the monitoring wells and the HDPE pipes was filled with bentonite.

Groundwater lowering with deep wells

By covering the fort zone and placing a cement-bentonite wall around the entire zone, a completely impermeable encapsulation was realised at the bottom, top and sides. Thus, no more water can enter or leave the encapsulated zone. The groundwater table inside the wall, however, still needed to be lowered to 1 m below the surrounding groundwater outside the wall. This was necessary to ensure that there was no hydraulic pressure from inside the cement-bentonite wall to the outside. It was not known what level should be taken into account outside the wall because no data was available. The water level inside the wall was also unclear after complete capping. Thus, measurement data from the monitoring wells, placed by Geosonda, was used to indicate the initial levels, and from this determine the final desired levels.

Installing the monitoring wells and collecting the measurement data afterwards had a major impact on the schedule. It was initially assumed that the action required regarding the groundwater lowering would have been clearer at an earlier stage. The final completion of the fort zone, within the cement-bentonite wall, was delayed because of the length of time that proved necessary to install and sample the monitoring wells.

To avoid too much delay, it was decided to install the deep wells before all the measurement data was known. After all, pumping could already be started without knowing the effective final level to be achieved. The location and depth of the deep-well pumps were determined by ABO nv based on the PID measurements that had happened during the installation of the monitoring wells by Geosonda. Indeed, it was important to ensure that the deep-well pumps were not placed in areas with floating or sunken layers. Also, an excessive level of pollution would be detrimental to the operation of the WWTP, or would simply make cleaning the water impossible.

Before installing the deep-well pumps, it was necessary to penetrate the liner. This was done in a similar way to installing the monitoring wells.

Once the pumps were installed, the heights of the pumps were optimised to minimise the pollution load on the WWTP. However, it was still necessary to expand the WWTP with additional filter elements and stripping towers to clean the water from within the fort zone.

Zone 2

TM - ABO

Zone 2 is the buffer pond used by the nearby company that uses the Scheldelaan drainage as a buffer for its treated water that eventually drains to the Scheldt.

Approach to drainage construction

Because of the difference between the high water level in the Scheldt and the level of the drainage sluice in the dike, the buffer basin serves as a buffer at high water, with the water from the buffer basin flowing into the Scheldt at low water. At the start of the works, the water drained away through a very outdated and deteriorating drainage structure. The valves in this structure were no longer impermeable so there was constant leakage of water to and from the buffer basin. The outlet structure was located south of the buffer pond and the inflow point to the north. Between 1,300 m^3 and 2,000 m^3 of water per hour is discharged into the buffer basin.

In order to carry out the works in the buffer basin, it was necessary to drain the buffer basin. Along the side of the Scheldt, a soil embankment was installed on the outside of the drainage structure. Image 42 shows the buffer pond at the top of the photo with the original dike below, the concrete structure that is part of the drainage structure and the new dike that separates the Scheldt from the buffer basin. In order to construct this dike, it was important to first remove the upper sagging layers of the reed bed. The works had to be carried out according to the tide in the Scheldt:

Img. 42 Large pond.

Img. 43 Cover with HDPE liner
and geosynthetic clay liners.

Img. 44 Site route through pond.

work could only be done at low tide until a certain height had been reached. Throughout the term of the works, this dike has had to be repaired or reinforced several times. To ensure the stability of the temporary embankment, temporary clayish soil and crushed stone were also eventually installed on the outside.

On the north side of the buffer pond, treated wastewater enters the pond through a concrete sewage that runs under Scheldelaan. The outflow structure at the end of this tube was blocked with a steel plate that was waterproofed along the edges. A pumping plant was installed to pump the water to the Scheldt, through a dredging pipe of about 250 m length. The entire pumping plant consisted of four pumps, each capable of pumping approximately 700 m^3/hr. Normal drainage then required two pumps to operate, extreme drainage required three. There was, therefore, at least one pump on standby at all times in case a pump broke down, blocked or failed. All pumps were controlled based on a float and the water level in the shaft. The plant was connected to the fixed power grid but a generator was on standby to take over automatically in the event of a power outage. The emergency generator was tested periodically to ensure that the pumps could continue pumping water in the event of a power outage.

The operation of the pumping plant was crucial because in the event of a failure, the entire buffer basin would fill up again and the works in the buffer basin would have to be stopped, the safety of the site personnel would be compromised and the works already carried out would be flooded.

Because guaranteed drainage of the water had to be assured, a final fail-safe system was built in, i.e. gravitational drainage at low tide through the dike into the Scheldt. A total of three dredging pipes with check valves were dug into the temporary dike between the Scheldt and the existing drainage structure. These dredging pipes would then take over the operation of the drainage structure (discharge at low water into the Scheldt) if necessary in the event of a failure of the pumps.

The dike between the Scheldt and the drainage structure was only fully closed in at very low water on the Scheldt, at a time when the buffer basin was thus completely drained. This meant it was possible to avoid having to drain the buffer basin.

Overall remediation approach to the buffer basin

The silt present in the buffer pond was not navigable for personnel or machinery. So, the buffer basin could not be covered with HDPE liner and geosynthetic clay liners in the usual way, where the rolls are unrolled from a frame attached to the arm of a hydraulic excavator crane.

An attempt was made to dry out the silt and although a dry crust formed, it did not provide a solution or improve the bearing capacity of the silt. Before the liner and geosynthetic clay liners were installed, an intermediate sand dike was created in the buffer pond. That dike was intended not only as a work platform in the buffer basin but also as a work coffer for the construction of the concrete trench that was to come into the buffer basin. The silt was excavated while sand was put in its place. Using the bucket of the excavator, the sand was pushed forward to push the silt forward. In this way, a cavity was created on the infill side and sand could be replenished in the clean zone [Img. 44]. The location of the sand dike, and thus the future concrete trench, was chosen at the site of a naturally emerged scour channel. The thinnest package of silt was present at this location.

The HDPE liner, and afterwards the geosynthetic clay liners, were pulled over the silt using a winch system. This included one hydraulic excavator on the work dike and one excavator on the edge of the buffer basin. One of the cranes held the frame containing the roll and the other crane pulled the HDPE liner or geosynthetic clay liner toward it. The largest span was about 100 m.

Once the liner was unrolled, it was possible to walk over it and the HDPE welders had access to the buffer basin. It was not possible to make any further corrections to the position of the liner once it was unrolled. Thus, the signalman had to continuously give signals to both excavator cranes during unrolling to ensure that the overlap between two adjacent pieces of liner was not too great or too small. If the overlap was not correct, the liner could not be joined. It was therefore opted to overlap slightly more and a piece of liner was then cut away along the edge. Cutting away a piece of liner along the edge, however, led to losses and lower efficiency.

Another important aspect was the weather. The liner could not bear a load until it had been joined together. Because of the large distances over which the liner had to be pulled across the buffer basin, work could not be carried out in windy conditions. Also, start-up was slower during rain since rainwater from all the surrounding embankments entered the buffer basin and had to be removed first.

On top of the HDPE liner, geosynthetic clay liners were unrolled in the same manner. These mats do not have to be attached to each other, but the minimum overlap still had to be respected when unrolling. The geosynthetic clay liners were pre-sprinkled with bentonite powder at the edges so that bentonite powder only needed to be sprinkled manually on the ends.

On top of the geosynthetic clay liners, a cover layer of soil was applied. The main function of the capping layer is to protect the underlying geosynthetic clay liners and HDPE liner. To avoid soil leaching, this had to be an oily soil (clay-like).

Although the buffer basin was accessible to people on foot because of the HDPE liner and geosynthetic clay liners, there was not yet enough bearing capacity to drive machines over the covered silt. Soil was applied to the geosynthetic clay liners with a long-reach excavator along the edges (embankments) and from the intermediate embankment in sand. All edges within the range of the long-reach, i.e. about 20 m, could thus be covered without entering the buffer basin.

For the further capping of the buffer basin, several options were considered, paying particular attention to the weight and ground pressure of the equipment to be deployed: mini-cranes with tracked dump trucks or compact tracked loaders. It was possible to drive these machines over the cover layer already in place, but problems occurred if these machines approached the edge of the backfill, where there was no back pressure on the HDPE liner and geosynthetic clay liners and no soil was present at the time. Completing the cover of the buffer basin with these machines therefore did not appear to be an option; there was a need for machines that could work far enough ahead to stay away from the edges.

Finally, small long-reach cranes were used (15-20 T) and timber mats were employed to reduce the crane's ground pressure. The timber mats always had to be moved with the crane so that only low yields could be achieved. The buffer basin could be well covered in this way and the final layer was applied across the whole surface area.

Construction of central channel in the buffer basin

The central channel, as mentioned earlier, was constructed in the sand dike in the buffer basin. The coffer was excavated **[Img. 45]** in the sand and thus no more silt had to be excavated at this stage. Before starting the concrete work, the coffer was lined with HDPE liner that was connected along the edges to the previously installed HDPE liner on the silt. In this way, the impermeable cover continues under the concrete trench. It was envisaged at the time of design that the current scour channel would be constructed as a concrete channel (to prevent further erosion). The statement of details and dimensions assumed an on-site unreinforced floor slab of 30 cm thickness and precast elements of 20 cm thickness on the sides of the trench. In the end, the choice was made to execute the entire trench (both floor and sides) with concrete poured on site. The poured floor slab was formed using liquid concrete, which was applied with a concrete pump, and dry concrete on the 2:1 slope which was, as much as possible, brought on site by machine (mini tracked dumper) and processed by machine (mini excavator). The dry concrete was finished manually on the sides and the sides were divided into sections about 4 m wide each time to remain workable. To this end, steel I-beams of 20 cm height were used as temporary edge formwork on which the concrete could be levelled. In this way, 'tiles' of about 4 m wide and 2.25 m high (measured along the slope) were created. To ensure that

Img. 45 Excavation of the channel.
Img. 46 Laying floor slab in the channel.
Img. 47 Laying floor slab in the channel.

Img. 48 Side of the channel.

Img. 49 Final result from the air.

these tiles would remain stable on the side of the trench, they were propped up behind the floor slab. To this end, when the floor slab was poured, a formwork was placed against the side of the trench, in the bend of the slope. After the demoulding of the floor slab, the tiles could be placed behind the floor slab in such a way that they were clamped. Images 45-49 show the different steps.

Problems and release of the 'bubbles'

While covering the buffer pond, bubbles were observed forming under the liner. Initially these were small bumps but as time went on the bumps became larger. After the buffer basin was put into operation, some of the bubbles had grown into real 'islands' that were no longer completely submerged when the buffer basin was filled.

To avoid making the situation worse and because the mini islands had a detrimental effect on the buffer capacity of the basin, it was decided to remove the bubbles.

The liner was cut open and the water trapped under the bubbles was pumped off and treated through the WWTP that was still present on-site. Since the buffer pond was already in use, these works could only be carried out during low water in the buffer pond. The closer to the central channel they were, the less time there was to work on them. After the water was pumped out of the bubbles, a conduit was joined to the liner. At the top, the conduit was also made impermeable. In this way, passages are provided to allow for the possible removal of water at a later date if the bubbles form again.

Zone 3 & 4

TM - ABO

Zone3

The northern and eastern banks of the buffer pond were contaminated in the solid part of the soil and, as a remedy, clean soils were used as a cover. A separating geotextile was installed as a warning for future (ground) work; clean soil is then placed on top.

Zone 4

During the study phase, contamination was identified in an area north of the fort. With regard to a safety margin, a larger area was then provided that had to be excavated, from a certain level, under the supervision of the environmental supervisor.

During the execution phase, several spots of waste and contamination were found outside the initially foreseen zone. Excavation of those spots and the contamination in zone 4 always required selective excavation. The environmental supervisor was always present to give directions. The soil was stockpiled according to the expected contamination and treatment method. The stocks were analysed and based on the results it was decided whether the soil could be reused or had to be treated off-site. Thus, general bulk excavation was interspersed with selective guided excavation in this zone. This had an impact on the planning, particularly for the various embankments, since the use of selective excavation meant that no more or less soil could be brought to the embankment zones. Thus, during the excavation and stockpiling of (presumably) contaminated soils, it was vital to continue bulk excavation in other clean areas so that the embankment work did not come to a halt.

Close contact between the environmental supervisor and the site management was crucial to the success of the earthmoving planning. This is due to the waiting period between taking the samples and obtaining the analytical results. So it was always a matter of waiting to see which stocks had to be treated off-site and which zones needed further excavation.Contaminated soil was removed and treated in approved soil treatment centres.

Civil engineering works

TM

The civil engineering works at the Fort Sint-Filips site could be divided into the following different components: **A.** damming wall up to +11 m TAW in three segments of 115 m, 150 m and 455 m respectively; **B.** new drainage structure buffer pond. In total, these works include some 350 T of reinforcing steel and 2,100 m^3 of concrete. Below is a brief description of these various works.

A. Damming wall up to +11 m TAW

The design provides for a concrete damming wall at three different locations to replace the standard type of dike for the Sigmaplan flood barrier. In the first two zones (north and south sides of the buffer pond), it was created due to design limitations of the dike body (see Sweco design). These were lengths of 115 m (south side) and 150 m (north side). Both segments are constructed in the same way:

- piling sheets type AZ13-770 to -6 m TAW;
- head beam 80 cm width x 100 cm height;
- wall 35 cm width.

The northern wall of 150 m was divided into eight legs with variable heights from 175 to 275 cm **[Img. 50]**. The southern wall of 115 m was divided into seven legs with variable heights from 175 to 500 cm **[Img. 51]**.

Img. 50 Civil retaining wall north.

Img. 51 Civil retaining wall south.

Img. 52 Civil retaining wall blue piling sheets.
Img. 53 Civil retaining wall blue.

Parallel to the construction of both retaining walls, prefabricated piles were inserted into the slope on the pond side to 'nail' the embankment. This involved approximately 100 piles on the south side and 150 piles on the north side with section 300 x 300 mm and lengths of 10 to 12 m (+3 m TAW to -9 m TAW).

The 455 m damming wall in the north of the site connects to an existing damming wall from a previous implementation phase and its function is to ensure the minimum required width of the future pipeline strip. Indeed, in this part of the site, there was no room for a traditional dike construction according to the standard cross-section. This 455 m long retaining wall was subdivided into 22 standard legs each 20 m long and one end leg 15 m long [Img. 52-53]. This wall had the same construction along its entire length:

- piling sheets type AZ20-700 to -6.5 m TAW (length 12.8 m);
- ground anchors 2.8 m centre to centre; 522 kN service load; 45° inclination;
- head beam 80 cm width x 100 cm height (from +6 m to +7 m TAW);
- wall 35 cm width x 400 cm height (from +7 m to +11 m TAW).

B. New drainage structure buffer pond

After the remediation works, the buffer pond had to be returned to service. To this end, the client decided to replace the outdated drainage structure with a new one. The new structure was built almost parallel to the current one, in order to make use of the existing drainage channel to the Scheldt as much as possible. The design consisted (as the old one did) of a single tube consisting of two segments, each with a cross-section of 150 cm width x 175 cm height and a total length of about 60 m. The functionality of the structure is ensured by HDPE check valves at the end of the structure. These close the tubes at high water level of the Scheldt and open at low water due to pressure from the increased water level from the buffer pond. In the centre of the tubes, a vertical shaft was also provided on top of the tube in which recesses were made to accommodate two spindle slides. These allow the buffer pond from the Scheldt to be closed manually.

Demolition of old construction

After performing the structural work for the new drainage structure, the old shaft was demolished. After removing the accessories (azobe bulkheads, etc.), the structure consisting of masonry and concrete was demolished using 35T crane with a hydraulic breaker. The debris was kept separated as much as possible and treated off-site.

Img. 55 Civil retaining wall UW.

Execution of building pit + difficulties in drainage due to pollution
Given the rather limited depth (+/- 7 m) and size, it was decided to carry out the construction in an open building pit. This was also possible due to the available space to excavate the construction pit under the embankment. However, upon excavation, the plan had to be partially adjusted and an additional tube wall screen was driven to ensure sufficient slope stability. This mainly at the head of the construction pit on the side of the temporary dike in the Scheldt. This sheet piling, in turn, provided additional protection for this temporary dike, which during execution was the only barrier between the Scheldt and the works.

C. Adaptation works sewerage Scheldelaan
The contract originally envisaged the construction of a second drainage structure specifically for the drainage of rainwater originating from the Scheldelaan. In fact, that water was also drained and buffered in the buffer pond before the works began.

Because of practical difficulties and the major interference with the existing pipelines, Port of Antwerp opted to remain connected to the buffer pond. To this end, the current sewerage system was extended some 15 to 20 m to emerge in the new embankment of the widened pipeline strip. It involved a sewer diameter of 1,000 mm with a prefabricated drainage element additionally equipped with a manual wall slider at the end. To avoid the leaching of fatty soil at the sewer outlet, an on-site poured drainage ditch was created up to the edge of the concrete central channel in the buffer basin.

Dike work

TM

The dike work formed a major part of the overall works. Over the entire area of the works, the dikes had to be raised and strengthened according to the regulations of the standard type of dike included in the Sigmaplan (see draft DVW). In total, this included approximately 1,900 running meters divided into two zones (Sigma-South and Sigma-North). The dike had to be realised on both south and north sides and had to connect to dike works from previous phases.

The following page shows the standard cross section of the new dike body to be applied. The structure on the water side is as follows:

- pine/oak piles L=2.5 m; 1 per m (top +5 m TAW);
- gabions 1 m x 1 m (top +5 m TAW) filled with crushed stone type CP 90-250 mm;
- oily soil with 1 m thickness on profiled 16/4 embankment;
- synthetic fibre cloth (geotextile type Terralys LF46);
- 0.75 m of crushed stone pavement type LMA60/300;
- cross dike consisting of built-up tow-path (finished level +11 m TAW).

Below are some key figures for realising the above dike works.

- length: 1,900 m
- crushed stone type LMA 60/300 kg: 85,000 T
- oily soil: 110,000 T

Img. 55 Unloading oily soil.
Img. 56 Unloading crushed stone.

For realisation of these dikes, good logistical coordination was an extremely important focus area. After all, there were two external supply streams (oily soil and crushed stone) which had to be well coordinated with each other and harmonised in time. Because of the large quantities required, both raw materials were brought in by water. Since there were no unloading facilities on the job itself, there was a search for a nearby quay that could be used for this purpose. This was found 5 km from the site. The ships were unloaded using a transfer crane and ground trolleys were used to cover the last few kilometres to the shipyard. In order to avoid creating unnecessary, intermediate stocks at the yard, efforts were made each time to use a just-in-time delivery method for the ships. For this reason, the final transport was carried out with trolleys instead of trailers so that the whole site was accessible. At the site itself, the raw materials were immediately received and processed by an excavator crane. When received, the oily soil [Img. 55] was simply dumped on the slope or embankment; for receiving crushed stone, [Img. 56] a drive-in pit was provided which was suitable for this calibre of crushed stone.

Fascine & anti-scour mattresses

TM

Around the head of the fort, the dike had to be additionally protected by fascine and anti-scour mattresses. Here, additional protection was placed on the slope over a length of some 200 m up to the low tide line, in order to prevent erosion in this heavily stressed zone.

Fascine mattresses are constructed from bundles of brushwood. These are bundles of willow twisted together and secured with biodegradable lashing rope to form mats. Fascine mattresses have been used for over 100 years to protect soil and banks from erosion by water. They can also be made with synthetic cloth: geotextile or bentonite.

For the delivery, installation and securing of these fascine mattresses, subcontractor Van Aalsburg B.V., a company specialised in these (niche) works, was called in. The mattresses were first fabricated on a suitable working platform (zate) near the waterline. From there, they were pulled into the water and then sailed into position by tug boat. The fascine mattresses were positioned by GPS and then slowly loaded with ballast made of smaller calibre stones to sink them [Img. 57-58]. After placement, a crane barge was then used to place the final crushed stone type LMA 60/300 on top of the mattresses [Img. 59].

Img. 57 Transport fascine mattress.

Img. 58 Placing fascine mattress.

Img. 59 Crane ship.

Earthworks

TM

The starting point for the earthmoving work to be carried out on the site was to achieve the most closed volume balance possible. That is, the design assumed that all soils in excavation could be used to the maximum extent possible to make all necessary additions to embankments. Thus, no or only limited external backfill soils had to be brought in or taken out. The entire work involved some 550,000 m^3 of earthmoving.

Here, good internal soil flow planning was very important. This boiled down to constantly coordinating earth movement in excavation and soil backfill to save unnecessary intermediate stockpiling and duplicate earth movement. The driving distances were also taken into consideration in order to draw up a good internal soil flow plan.

An additional difficulty here was that the entire project area was divided into five separate contract sections, each with a separate award and start date. Thus, the largest earthmoving works could only be started after the commencement order of VD3 - Construction Crib and VWD2 - Sigma Works North. These sections were, in fact, mainly sections in replenishment while the other contract sections were mainly sections in excavation. So the overall planning of the entire work had to involve the various contract parts.

Actually, the largest ground flow, from south to north, was intended to realize the Crib and associated backfill between Scheldt Dike and Crib Dike and is further explained in a separate section.

To ensure the continuity of the works, one specific set of earthmoving equipment was chosen at the start of the works to move the 550,000 m^3 of soil. That set was specifically provided for earthmoving. Other works (dike works) were carried out with other equipment. The fixed set of equipment usually consisted of a 40 to 50 T excavator, 3 to 4 40 T dumpers and 1 bull D6, which could achieve a daily production of +/- 3,000 m^3.

Crib Construction

TM

An essential part of the combined earthworks and dike works involved the realisation of an additional dike in the Scheldt, further called Crib (Kribbe) (see explanation DVW). The construction of this Crib consists of the following parts and the type of section below.

- dike core of soil from the site;
- protection of slope using geobags (geotextile elements);
- fascine & anti-scour mattresses;
- crushed stone type LMA60/300 kg;

The new dike to be constructed was about 400 m long and had the additional difficulty that the level was below the high water line, namely +3.5 m TAW at the start of the dike and 0 m TAW at the end of the dike. Therefore, in order to realise the works, an overhang was first created so that the temporary dike would always be located above the high water line. This allowed work to continue through the tides. The Crib was broadly realised according to the methodology below and is further illustrated by the attached photo report **[Img. 60-75]**.

Img. 60 Creating ground dike.

Img. 61 Creating ground dike.

Img. 62 Placing geotextile elements after profiling dike.

Img. 63 Placing geotextile elements after profiling dike.

Img. 64 Placing geotextile elements after profiling dike.

Img. 65 Prefab zone fascine mattresses.

Img. 66 Prefab zone fascine mattresses.

Img. 67 Prefab zone fascine mattresses.

Img. 68 Sailing in fascine mattresses.

Img. 69 Sailing in fascine mattresses.

Img. 70 Placing and ballasting fascine mattresses.

Img. 71 Depositing crushed stone.

Img. 72 Depositing crushed stone.

Img. 73 Elimination of over-height (infill between Scheldt and crib dike).

Img. 74 Elimination of over-height (infill between Scheldt and crib dike).

Img. 75 Elimination of over-height (infill between Scheldt and crib dike).

Environmental monitoring of remediation works

TM - ABO - DVW - POA - SWECO

The remediation work was carried out under the supervision of certified soil remediation expert ABO nv. ABO nv verified that the remediation works were carried out in accordance with the soil remediation project. In this, it formed an important link between the clients for the works on the one hand and the remediation contractors on the other. In addition, ABO nv also took care of the contacts with OVAM, the government agency responsible for the control and supervision of remediation works.

Below, some of the major subtasks of environmental monitoring during this project are explained.

Mapping before works begin

Before the insulation (cement-bentonite wall) could be installed, the perimeter line for the insulation had to be accurately determined. To the south and west, the isolation was bordered by the Scheldt River and to the east by the buffer basin. However, in the northern direction, there was a degree of uncertainty on the most optimal location of the wall.

Three mapping campaigns took place during which borings were carried out to determine the boundary of the core zone. This was done prior to the actual start of the remediation works, but only after the removal of vegetation and the levelling of the site. Poor accessibility to the site was the main reason why no conclusive mapping could be carried out in the earlier investigation phases. The final location of the northern perimeter line of the cement-bentonite wall could be determined based on the results of the mapping. The final perimeter and area turned out to be slightly larger than estimated in the soil remediation project: 27,183.69 m² instead of 22,022.7 m².

Follow-up of selective storage and disposal of cement-bentonite sludge

Much of the soil released from the installation of the cement-bentonite wall was heavily contaminated. However, the contamination was not homogeneously distributed; some zones contained no contamination or very little. In order to optimise the disposal of soils, an excavation plan was prepared in which the soil released from the trench for the cement-bentonite wall was classified into four different categories, according to the expected treatment possibilities.

During the works, samples were periodically collected from the soil that was released. This excavation plan was constantly adjusted based on organoleptic observations at the site and the analytical results of the samples.

The excavated soils were selectively stockpiled in batches of similar quality. Final treatment options were determined for each batch based on additional mixed samples from the stockpile basins where the batches were stored. In this way, non and moderately contaminated soils were prevented from becoming mixed with heavily contaminated soils, and unnecessary treatment costs could be avoided.

Follow-up of selective excavation in contamination zone 4

Contamination zone 4 involved a separate core with BTEXN and volatile mineral oil. The concentrations were of a lower order of magnitude than those at the level of the fort or in the buffer basin. However, because the area around zone 4 was located outside the Sigma dike, and had to be excavated below the level of the Scheldt, a more drastic remediation by means of excavation was necessary at this location.

The contamination was mapped in previous phases of investigation, but there were some conflicting results that suggested that the actual excavation contour could possibly differ from the anticipated perimeter. Trial trenches were dug at the start of the remediation to conduct additional sampling to refine the excavation contour. The results were not entirely clear and, at the start of excavation, the situation did not appear to match the assumptions based on the trial trenches. The excavation was further managed by sampling the pit sediment and walls from the actual excavation zone. The soils were briefly stored at the site after excavation, being subdivided into different batches according to their suspected quality/treatment potential. A sample was then taken for each batch to determine the exact quality analytically and to select the treatment method.

Installation of monitoring wells

To monitor the effectiveness of the isolation around the fort, a network of monitoring wells was installed. 63 monitoring wells were installed, spread over 16 clusters each with monitoring wells in 3 to 4 different filter positions, from intersecting with the groundwater table to just above the Boom clay (around 20 m TAW, ca. 30 m-mv).

Periodic monitoring of this well network should enable follow up to ensure that the contamination within the walls has effectively stopped spreading and has indeed been isolated.

When the monitoring wells were installed, undisturbed soil samples were also taken which served as control samples to record residual contamination both inside and outside the cement bentonite wall. To combine qualitative sampling and monitoring well placement, within a feasible time frame, it was decided to place the monitoring wells using the roto-sonic drilling technique.

Water treatment plant follow-up

At several points during the remediation, it was necessary to extract and drain (ground) water. Given the level of contamination, this required that the water be cleaned before discharge.

ABO nv was responsible for the monitoring of the WWTP, in particular for checking whether the effluent concentrations met the imposed discharge conditions. In view of the high pollution load in the extracted water, the installation had to be adjusted several times. In order to facilitate optimisation of the process and to be able to make targeted adjustments, a detailed follow-up of the WWTP was carried out: samples were not only collected at the level of influent and effluent, but also after all individual purification steps. This allowed for targeted adjustment of certain components of the WWTP to obtain maximum treatment efficiency.

General follow-up of the progress of works

ABO nv was responsible for documenting all remediation work throughout the project. To this end, there was almost continuous supervision for the bulk of the remediation period. An environmental supervisor from ABO nv conducted several site tours a day and noted progress, findings and recommendations. This was then compiled into a daily environmental diary, which also held data such as analyses of control samples and run-off volumes. This diary was circulated to all parties on the following day, so that everyone was kept informed of the progress of the work at all times and adjustments or additional consultations could be made where necessary.

The remediation involved various types of work where the actual environmental follow-up - in the sense of sampling, analysis and adjustment - is limited. Examples include the construction of the impermeable top cover above the fort, the capping of the buffer basin, and the habitat remediation around the buffer basin. In doing so, however, it was still important to have a follow-up to document the progress of the works and ensure that the various remediation measures were carried out in accordance with the provisions of the soil remediation project.

Reporting

ABO nv was also responsible for the official reporting of the remediation works to OVAM. Two concise interim reports were prepared during the works to inform the OVAM of progress and certain technical changes compared to the soil remediation project.

An overall interim report will be prepared in 2022 that will describe all the remediation work, with the exception of the monitoring wells follow up. This monitoring will be continued for at least three years before final reports can be submitted. The final reporting of the completed remediation will follow in a final evaluation study, now scheduled for 2025.

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Management & Monitoring

Crib

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Crib

In order to gain a good overview of the impact of the construction of the Crib, a monitoring plan was drawn up by Flanders Hydraulics and the INBO in June 2018 and the first measurements were then carried out (T0 or zero situation before the works and a T1 just after the works).

In addition to its essential function as an 'engine' to develop tidal nature, the Crib also has an important function as a pilot project. As part of a comprehensive multidisciplinary study on future developments in the Zeeschelde (Integral Plan for the Upper Zeeschelde), the possibility of carrying out similar interventions at additional sites is being considered. Monitoring for up to five years after the works are complete will teach us more about the sustainability of the intervention, the effects on morphology in the vicinity of the Crib and the development of tidal nature around this pilot project.

Initial multibeam measurements are already showing some significant effects on the morphology around the Crib. For example, due to the cutting of the highly dynamic secondary channel, upstream of the Crib, a great deal of additional accretion to mud-flat level has already been observed. A first report of the results is expected during 2022.

H

Evaluation

Key figures

General: Duration of works: *mid-October 2019 - end of January 2022*; Number of machines deployed: *variable, but at peak 15 to 20 machines*; Staff on site: *variable, but at peak 5 to 6 project team members (1 project manager, 1 work planner, 3 site managers, 1 surveyor), 30 to 40 workers.*

Remediation: Isolation volume: *27,000 m^2 x 30m depth = 810,000 m^3*; Volume of cement-bentonite used: *20,000 m^2 surface area of CB wall*; Surface area of HDPE liner used: *62,500 m^2*; Groundwater purified: *12,000 m^3*; Soil cleaned: *60,000 T (treated off-site).*

Earthworks: Volume of soil reused: *500,000 m^3*; Volume of crushed stone applied: *85,000 T*; Area of willow mats: *14,000 m^2*; Volume of geotextile elements: *15,500 m^3*.

Construction works: Volume of concrete used: *2,100 m^3*; Volume of steel: *350 T*; Number of running meters of ground anchors: *160 ground anchors of lengths 28 m to 36 m.*

Results: Tidal nature created: *18.2 ha*; Pipeline strip widened: *1,790.64 m*; Length of tow-path: *2,102.85 m + 2,096.18 m + 3,216,23 m.*

Financial

Strategy and communication plan	Estimate 2019	Tender 2019	Cost 2021
Works AZZ-19-0015			
Remediation component	9,641,000 €	10,630,000 €	10,797,652,27 €*
Sigma Works component	7,415,000€	7,422,000 €	8,174,864 €*
Pipeline Strip component	1,791,000 €	1,845,000 €	1,948,37 €*
Total works	**18,847,000 €**	**19,897,000 €**	**20,920,896€***
Financing works (%)			
Financing DVW	—	—	34.9%
Funding POA (incl. third party funding)	—	—	60.3%
Financing Interreg	—	—	4.8%
Services			
Sweco study	203,625 €	121,601 €	130,813 €*
Study ABO nv	361,785 €	447,020 €	391,153 €*
GEOSONDA services	187,270 €	146,910€	136,802 €*
Total Services	**752,680 €**	**715,531 €**	**658,768 €***

*To date 31/10/21

The final cost consisted of: cost of works; cost of revision / COVID measures; cost of additional works.

Lessons Learned

Preparation

A number of choices were made during the preparation process that greatly determined the project course and especially the timing.

The cooperation from the start of the project definition between DVW and POA helped to integrate the objectives and preconditions of both organisations and enable business cross-pollination of added value in a very cost-effective way. This continued through to the final delivery of the works and the many peripheral aspects of the project such as ownership and management agreements and joint communication actions. It also facilitated smooth coordination with pipeline operators and industrial players impacted by the works.

Working with a global permit for the four zones with a phased implementation undoubtedly saved us a great deal of procedural time. The preparation of the permit application probably took a few extra months initially, but having to go through the entire procedure four times would have delayed the execution by dozens of months, at least, particularly taking into account the changing Flemish procedures between 2015-2020, such as the Archaeology Decree, the introduction of the Digital Desk (with its many teething troubles) but also the amount of extra drawing work that these different permit files would have entailed. It also gave us the opportunity to look at the nature impact and the nature goals set out across the four zones, rather than using a piecemeal approach.

During the tender process, the added value of an explanation during the publication period also became apparent. This allowed ambiguities for the contractors to be clarified and the most important points of interest from the clients to be provided. This greatly increased the quality of the bids

Design

Despite the lengthy contract (from 2013) and the many replacements of engineers who worked on it, the integral design and consulting during execution led to a correct result. Lessons learned from one zone (e.g. in relation to settlements of certain layers) could be smoothly implemented in the other zones. The coordination between ABO nv and Sweco occurred smoothly, although it was noted that there were some minor areas for improvement in the drafting of the tender document. Coordination at this stage was rather limited. This relates to the typical time constraints on clients for finishing the tender document.

Implementation

The complex nature of both the remediation works and the Sigma works proved to be a tough challenge for all parties. Thanks to smooth and intensive cooperation between all parties involved and a transparent attitude in connection with bottlenecks, problems and sensitivities specific to each organisation, the works and the many unforeseen changes were dealt with quickly and decisively. As a matter of principle, most problems encountered during execution were first discussed on site (usually the moment of action itself) and practical solutions then worked out in concert. The daily coordination of ABO nv and the principals with the contractor combination was therefore crucial to the success of this project. The adjustments during execution took various forms:

- rock massifs in the substrate when cement-bentonite wall and HDPE liner are inserted;
- heavily contaminated groundwater outside the isolation contour at drainage construction pit;
- pollution load of the water to be purified higher than water treatment capacity;
- refusal to remove contaminated silt and floating layer in the fort roads not treatable resulting in additional inclusion of contaminated silt in the isolation contour;
- leaching of bank due to local erosion in transition zone anti-scour mattresses/gabions;
- unexpected gas bubbles in the buffer basin under capped contamination.

The many necessary adjustments in execution were further made possible by the flexible use of equipment and personnel by the contractors and the rapid evaluation and study by Sweco and ABO nv. It was precisely because of the complex combination of different remediation, earthwork and construction works that it was possible to use the same machines or personnel locally in different areas and thus increase efficiency when making adjustments to the schedule. Even the effects of the coronavirus (and measures) failed to delay implementation. Given that work was always being carried out on many fronts at once, it was possible, for example, to accommodate the loss of a shift due to corona quarantine in the planning.

During implementation, the drone flights and regular measurements offered significant added value. Not only for communication purposes, but also for gradual follow-up of the progress on site.

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Editorial
Astrid Verheyen
Michaël De Beukelaer-Dossche

Authors
Astrid Verheyen (Port of Antwerp), Johan Braspenninckx (Port of Antwerp), Gilles Trenson (Sweco), Steff Van Cauwenberg (DEME Environmental), Steven De Coen (Jan De Nul), Jan De Vos (ABO nv), Michaël De Beukelaer-Dossche (De Vlaamse Waterweg nv), Karen Minsaer (City of Antwerp).

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