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# Reclamation on Soft Subsoil by Spraying Thin Layers of Sand: The "IJburg" Project near Amsterdam

## Abstract

The question is often raised: "How can a stable platform be created during the reclamation of sand on very soft subsoil without having to remove the soft subsoil nor having to place large amounts of geo-textiles?" This article describes the experience gained during the successful reclamation of the first 200 hectares (2,000,000 square metres) of the IJburg project, east of Amsterdam, The Netherlands.

Besides a general overview of main features of the project and its design, the article will deal in particular with: geo-technical experiences; sand excavation and clay relocation at the borrow area; sand reclamation through spraying in thin layers; and planning aspects.

One main achievement of the project design and execution was the method of reclamation through spraying thin layers of sand. This was realised with the use of a custom-built spray pontoon, able to reclaim layers of predefined thickness with the help of computer-controlled winches. This sophisticated new way of reclamation, reaching high accuracies, made it possible to reclaim sand on very soft subsoil without having to excavate the subsoil and without having to place geo-textile on top of the existing subsoil. Because the subsoil was left in place, no storage area for unsuitable soil was needed and, as another beneficial consequence, less sand was needed for reclamation. During actual execution no major instabilities or other irregularities occurred, thus realising an economic way of reclaiming soft soils.

During the actual reclamation constant geo-technical monitoring and evaluation were carried out.
This enabled the designer to make adjustments as necessary.

A second achievement was the method of sand excavation at the borrow area in the lake Markermeer. This method combined the excavation of sand needed for the reclamation and the deepening of an existing shipping lane into one simple "train" of dredging activity. The problem that had to be solved was the presence of a large volume of clay overburden on top of the sand. This clay had to be removed, but no areas or basins for temporary storage were available in the near vicinity. Through the so-called "clay relocation method" this problem was solved.

Thanks go to Dick Sellenraad at Aeroview B.V., Rotterdam for the aerial photographs of the IJburg project in progress.

## Introduction

The demand for new housing areas in the Amsterdam region is high: about 100,000 houses will have to be built between 1995 and 2005. The region has limited space available for housing, however, and new options have to be weighed constantly. In the 1960s and 1970s there was a housing construction boom in growth centres in the vicinity of Amsterdam, like Purmerend, Hoorn and Almere. These growth centres are situated at a distance of 15 to 30 kilometers from Amsterdam and are home to many residents. Since many of them commute to Amsterdam for work, the overspill has caused traffic jams. In spite of improvements to the public transport system and expansion of the road structure, traffic jams remain a persistent problem. Besides causing delays and aggravation, they also are an increasing source of pollution. This overspill has also led to de-population of the city.

Consequently, in the 1980s, emphasis shifted to construction within the city. In the past few years, Amsterdam has built many new houses in urban renewal districts, former industrial estates and harbour areas. The available sites have been more or less used up. New building sites have been sought in the direct

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E.P.T. Smits

Edwin Smits studied Engineering Geology at the Technical University of Delft, and since 1990 works for the soil mechanical and environmental investigation and research bureau (Omegam) of the public works department of the City of Amsterdam. He worked as a geo-technical advisor and was involved in all aspects of the land reclamation of IJburg, from the feasibility studies up to the final reclamation and monitoring. Since July 2002, Mr Smits is a geo-technical advisor for the public works department of the City of Rotterdam.

F.A.J.M. Mathijssen

After receiving his master degree in Civil Engineering from the Technical University of Delft in 1998, François Mathijssen worked at Hydronamic, the engineering department of Royal Boskalis Westminster nv. Specialised in soil mechanics and foundation engineering, he worked as a project engineer and geo-technical advisor. Since 1998 he has worked periodically as a geo-technical advisor for Combinatie IJburg involving feasibility studies, optimisation of the reclamation process, reinforced soil structures and interpretation of monitoring results.

A.L.Ph. Estourgie

Alessandro Estourgie graduated from the Technical University in Delft in 1983 with a MSc in Civil Engineering. From 1983 to 1985 he worked on the Oosterschelde (Eastern Scheldt) storm-surge barrier project for the Dutch Ministry of Public Works. From 1985 to 1992 he worked for Volker Stevin Dredging on R&D and as project engineer. In 1992 he joined Ballast Ham Dredging, where he has worked as contracts and operations manager in the Singapore area and is presently a project manager for the IJburg project.

*Figure 1. Opposite page, pictures taken from the 200 hectares reclamation site "IJburg" around start (28 March 1999) (above) and after completion (24 June 2002) (under) of the first phase of the project. Both pictures offer a view in the Northwest direction towards the city of Amsterdam. Sand was reclaimed on existing very soft subsoil in several thin layers by a computer-controlled pontoon with high accuracy. This method enabled the designer to leave the subsoil in place and to omit placement of large amounts of geo-textile on top of the existing subsoil.*

vicinity of the city. It is crucial that these districts will be easily accessible by public transport. Eighteen potential sites have been evaluated to determine their suitability for housing. The sites have been weighed on the basis of four main aspects: the surroundings, support of the city, costs and completion, and mobility. IJburg was selected, as it fits in with urban planning policy on traffic control, environmental care and support to the city. In Figure 1 aerial overviews of the project can be seen.

Various plans (Figure 2) have been developed since this decision. The plans varied from reclamation of the complete lake to a partial reclamation of the lake. This partial reclamation consisted of several islands "IJburg" and was adopted. The plan foresees creation of 450 hectares of surface and therefore around 25,000,000 cubic metres of sand to be reclaimed in two phases (Figure 3).

In The Netherlands many land acquisitions have been realised as polders, which are therefore below water level. However IJburg was designed to reclaim above water level. This will offer the future residents direct visual contact with the areas around IJburg. In the past centuries several islands have been reclaimed above water in the former estuary "IJ", therefore one can say that the project IJburg is within this tradition of "reclaiming above water level". The difference with the islands made in past centuries is that for the IJburg project the subsoil is extremely soft and the time in which the project had to be completed was limited. At some locations the soft subsoil even reaches to a depth of 30 metres (an old Pleistocene glacial estuary). At such locations no reclamation is foreseen.

The importance of public transport is strongly reflected in the design. A light railway transport system will be constructed that can reach the city centre of Amsterdam within 18 minutes. Within several years a second link will be made that will be connected to the subway system in the south of the city. The future roads will give direct access to the highways around the city.

In the period December 1998 to April 2000 and the period October 2000 up to January 2002 dredging and reclamation activities (reclamation of over 10,000,000 $m^3$

of sand) took place for the creation of the first phase consisting of two islands of the project IJburg. The location is indicated on Figure 4. The employer for this project is the Municipality of Amsterdam, represented by Gemeentelijk Grondbedrijf Amsterdam. The final design, contractual procedures and the daily supervision of the project were delegated to engineering company Ingenieursbureau Amsterdam, whereas geo-technical advisory services were obtained from geo-technical engineering companies Omegam, based in Amsterdam, and Hydronamic, based in Papendrecht, The Netherlands.

Actual execution of the dredging and reclamation works was contracted by "Combinatie IJburg", a joint venture consisting of three Netherlands based dredging companies namely Boskalis, Ballast Ham Dredging, and Fernhout Aannemingsbedrijf. The reclamation works completed until now (first phase) were contracted by Combinatie IJburg through three separate and consecutive tender procedures.

Works on bridges, shore protections, roads, buildings and infrastructure completed by other contractors will not be described here.

*Figure 2. Plan "Bakema 1965" (top) and under, the "Islands of IJburg" plan.*

*Figure 3. IJburg (in yellow) is situated between the city, water and rural areas. In the design the relation between the new housing area and the existing city on the west side, the water on the east side and the rural areas on the north and south sides have been taken into account.*

## Main Features of the Project and its Design

**Bathymetry of the reclamation site**

A bathymetric survey of the area that had to be reclaimed revealed the depth of the water varying between 0.50 metres and 3.00 metres below NAP (NAP equals about average water level). This can be regarded as a very shallow area. Moreover during prevailing winds from the southwest direction the level of the water can be reduced by up to one metre, leaving only 50 centimetres of water in large areas. The subsoil characteristics show extreme weakness. The soil will be subject to considerable consolidation in the course of time and the stability is limited.

**Final design aspects**

In order to test and optimise the preliminary design, dating from around 1990, and in order to test various reclamation techniques, a pilot project near Amsterdam was carried out in 1995 that resulted in the formation of an island with a surface of around three hectares (Figure 6). Based on experience from this pilot project the final design was completed and contractual requirements were defined.

The final design is subdivided in several smaller design units of which the planning runs parallel with the planning for the construction of the housing. For each unit a separate design, consisting of many drawings, reports and calculations, has been made.

The final design deals with the following ten aspects as described below.

*1. Settlement requirements*

The periods in which the majority of settlement has to be reached are defined. Areas where infrastructure is planned should reach this settlement within 300 days. For housing areas this period is 600 days. Twenty-five years after these periods a residual settlement of only 20 centimetres is predicted. Total settlement will vary, depending on the location, between 1 and 2 metres.

*2. Design level*

The final design foresees that a building platform (ground level) will be realised of around 1 metre above NAP. This level was decided upon after considering the permeability parameters of the sand to be reclaimed. The groundwater was allowed to reach 50 centimetres below ground level only once in every two years. To reach this requirement, sand was selected and used with a K value of 7 metres per 24 hours.

*3. Volume of sand needed for reclamation*

The volume was calculated from the existing ground level, the future ground level, the predicted and measured settlements, and the amount of surcharge sand needed.

*4. Sand excavation*

Sand was excavated in the lake Markermeer, 25 kilometres from the reclamation site as shown in Figure 4.

*5. Temporary shore protection*

The shorelines were widened and heightened to create safety zones against natural water and wind erosion and in order to create the possibility to construct the final shore protection in a dry environment.

*6. Accelerating consolidation*

To accelerate consolidation, synthetic vertical and horizontal drains were applied. The triangular grid for the vertical drains varied from 1.00 to 2.50 metres and the length of the drains was 9 metres on average. Placement of sand surcharge was applied to further accelerate consolidation.

*7. Geo-textiles*

The controlled way of spraying sand meant that in only 5% of the area (only parts of the shoreline of the reclamation site) geo-textile had to be placed underwater before start of reclamation. This meant that on 95% of the area the sand was reclaimed directly on the soft subsoil without the need for geo-textile placement. The geo-textile will spread the load onto the subsoil evenly.

On the northern part of the island Steigereiland, at a level of 50 centimetres above the waterline, placement


*Figure 4. Location of the reclamation site and the sand borrow area. The sand borrow area is located at a distance of approximately 25 kilometres from the reclamation site IJburg. The islands reclaimed are named “Haveneiland” (Harbour Island) and “Steigereiland” (Jetty Island), and their surface, some 200 hectares, creates a building platform mainly for residential housing. Together they form the first phase of two phases of reclamation. The second phase will likely be realised several years later. Both phases are indicated in Figure 5.*

*Figure 5. Sketch of the IJburg project showing Phase 1 and Phase 2 of the development. The first phase (200 hectares) has been reclaimed and is described in this article. The second phase (another 200 hectares) will be reclaimed at a later stage.*

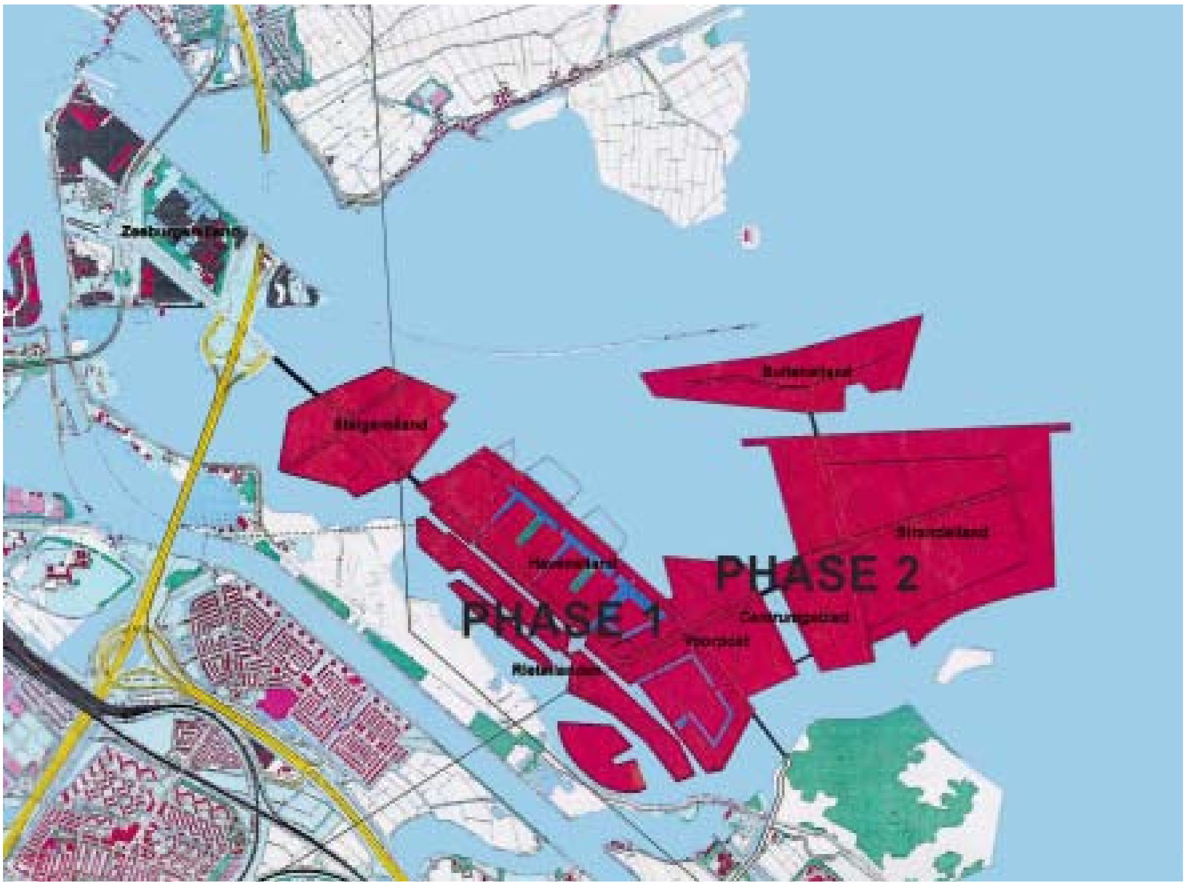


*Figure 6. Aerial view of the island with a surface of three hectares which was created during the pilot project in 1995. Photograph was taken on 6 January 1999.*

of geo-textile (type PET 400 / 50 kilo Newton tensile strength and maximum 10% elongation) on already reclaimed sand was necessary to reinforce the island. See also Figure 10.

*8. Reclaiming by spraying in thin layers*
Because of the availability of techniques to spray in thin layers, the designer chose to leave the subsoil in place and let it consolidate (instead of removing subsoil). A consolidation period of 4 weeks had to be allowed between each layer. The technique of spraying was developed and tested during the pilot project mentioned earlier.

*9. Precautions against wind erosion of the reclaimed area*

*10. The total cost of the project*

**Contractual aspects**
After approval of the design, contracts were made which were used for public tendering purpose according to European EG regulations. The contract was written by Ingenieursbureau Amsterdam in the RAW system. This system was developed in The Netherlands for the road building industry. Thereafter it was applied to most civil engineering contracts as well. A large number of standard texts that describe activities and contract conditions are available to the contract writer in this RAW system.

A complete digital library exists and is updated and adjusted constantly to reflect experiences on various contracts. The system allows the designer to write a new contract in an efficient way. The total contract sum is split up in practical and measurable units that enable an accurate and realistic payment schedule throughout the contract.

Some features of the IJburg contract are as follows:

- Reclamation had to be performed by spraying thin layers of only 50 centimetres (building of "large pancakes of sand"). Contractual tolerances were +/–10 centimetres.
- A consolidation period of minimum 4 weeks for each separate reclaimed layer was obligatory. This was to guarantee local stability of the subsoil. Average and maximum production levels were defined in the contract.
- The employer made the sand borrow area available to the contractor through arranged licenses. The contractor was made responsible for mixing the finer and coarser sand layers in such a way that the contractual required sand characteristics were realised.
- The contract limits the minimum and maximum sand production allowed per week to safeguard stability of the subsoil.
- The final reclaimed volume of sand is measured at the site of reclamation. Intermediate monthly volumes were measured in the transport barges and were invoiced as a preliminary to the final measurement on the reclamation site. Final calculation of the sand volume on the reclamation site was performed through SPT-measurements, executed by an independent laboratory, after completion. These SPT-readings (cone resistance and friction ratio) show a clear transition between the original soft soil bed and the newly reclaimed sand layers. This transition could be defined with an accuracy of a few centimetres, thus the thickness and volume of the sand layer could be calculated very accurately.

Main contractual requirements with respect to environmental impact are as follows:

- Damage to the environment is often caused by presence of fines (suspended solids) in the run-off water from the reclamation process. Life in the surrounding water would then be jeopardised. Therefore environmental restriction was imposed on the surplus-water (run-off water) flowing back in to the surrounding water. A maximum of 400 milligrams of suspended solids per liter of run-off water was allowed. Three large settlement basins (see Figure 7) together with high-flow water pumps were constructed and installed to be able to meet this very stringent requirement. At regular intervals water samples had to be taken and analysed by laboratories. The three basins succeeded in meeting the 400 milligram requirement.
- The volume of water pumped weekly by the cutter suction dredger and the barge-unloading dredger had to be measured and reported. It was not allowed to exceed weekly volumes mentioned in environmental licenses and in the reclamation contract.
- Birds immediately used the newly reclaimed sand for breeding purposes. For this reason, now and then, certain areas were closed for construction and reclamation activities. This was closely coordinated by ecologists.

For the contractor it was particularly challenging to minimise delays for the complete dredging spread while at the same time respecting these technical and environmental requirements mentioned above.

**Main activities during project execution**

At the sand borrow area (on average 25 kilometers remote of the reclamation site) over 9,700,000 cubic metres of clay had to be removed by cutter suction dredger. This 8-metre-thick clay layer (overburden) was present on top of the sand at the extraction-borrow area. Directly following this clay removal, extraction of sand to a depth of 25 to 30 metres and simultaneously filling of transport barges was carried out by the deep suction and barge-loading dredger Faunus, as shown in Figure 8.

After sailing to the reclamation site the barges were emptied and the sand was pumped through a maximum of 4,000 metres of pipelines (70 centimetres diameter) by a 14,000 HP barge-unloading dredger Sliedrecht 26. In this way over 4,000,000 cubic metres

*Figure 7. Three large settlement basins, containing nearly stagnant water, were specially constructed on the south side of the island Haveneiland to reduce the amount of suspended solids in the run-off water. A maximum of 400 mg/liter only was allowed. Given the normal content of fines in the sand this was a very stringent requirement. The water was directed into these basins by two high flow water pumps. Photograph was taken on 7 December 2001.*

Figure 8. Deep suction and barge-loading dredger Faunus excavating up to 30-metre-deep sand at the borrow area (approximately 25 kilometres distance from the reclamation site) and at the same time loading transport barges of 2,000 cubic metres volume each. The sand dredging process was often disturbed as a result of the presence of clay lenses in the sand. Photograph was taken on 18 January 2002.

Figure 9. The barge-unloading dredger Sliedrecht 26 emptying barges and pumping the sand through 4,000 metres of pipelines, consisting of submerged, floating, bridge founded (lefthand side of this picture) and shore-based stretches. In the background, 8 installation rigs for vertical drains can be distinguished. Also to the right, a part of the newly constructed access bridge to Steigereiland can be seen. Photograph was taken on 15 August 2001.

*Figure 10. To reinforce the reclaimed sand, approximately 130,000 square metres of geo-textile were placed on Steigereiland in 7 days, at a level of 50 centimetres above the waterline. The geo-textile applied was of the type PET 400 / 50 kilo Newton with 8% elongation, well within the required 10%. It was delivered to site in rolls of five metres width. On the reclamation site the textile had to be sewn together by handheld machines over a length of 30 kilometres. Photograph was taken on 21 August 2001.*

of sand was sprayed in layers with varying thickness (20 to 50 centimetres) by means of a fully automated "spray-pontoon" and about 6,000,000 cubic metres of sand was reclaimed in thin layers by conventional methods using a "quick-coupling system". Weekly a volume of around 100,000 cubic meters of sand was produced. In Figure 9 the dredger can be seen positioned opposite Steigereiland.

As soon as a level of 50 centimetres above the waterline was reclaimed installation of in total 8,300,000 metres of prefabricated synthetic vertical drains started. Maximum production reached was 350,000 metres per week with nine installation rigs. Installation of these drains included pre-drilling activities whenever necessary. On some locations geo-textiles (250,000 square metres in total) were installed in order to reinforce the construction.

## Geo-Technical Aspects at the Reclamation Site

**Subsoil characteristics at the reclamation site**

The subsoil was investigated drilling boreholes at a 200-metre grid in the Pleistocene sand. At critical spots and discontinuities this grid was densified with additional boreholes and CPTs. Further in-situ field-vane testing was performed to determine the undrained shear strength profile.

The top elevation of the subsoil in the lake IJmeer from the Western to Eastern sides of IJburg varies between, respectively, 0.5 metre below NAP (NAP equals about average water level) and 3.0 metre below NAP.
The watertable in the lake varies between 0.2 and 0.4 metre below NAP in, respectively, summer- and wintertime.

An extremely soft young Holocene clay-layer with a thickness up to 4 metres is overlying the Holocene peat and clay layers. These Holocene layers vary in thickness in the IJburg area between 6 and 12 metres. The geological history of the area is rather complex resulting in a large variability in the soil profile. The maximum measured thickness of the Holocene layers outside the IJburg area is around 30 metres, as a result of accumulated Holocene sediments in a Pleistocene estuary. The thickness of the young Holocene top layer varies highly over the area and is less in the southeastern part of IJburg (0–1 metre).

The Pleistocene sand is located at different depths in the western and eastern part of IJburg, namely 13 metres below NAP and around 9 metres below NAP, respectively. The zone with the extreme Holocene layer is clearly visible in Figure 11.

For both the construction stability as well as the consolidation and settlement behaviour of the reclamation, the young Holocene clay layer at the top

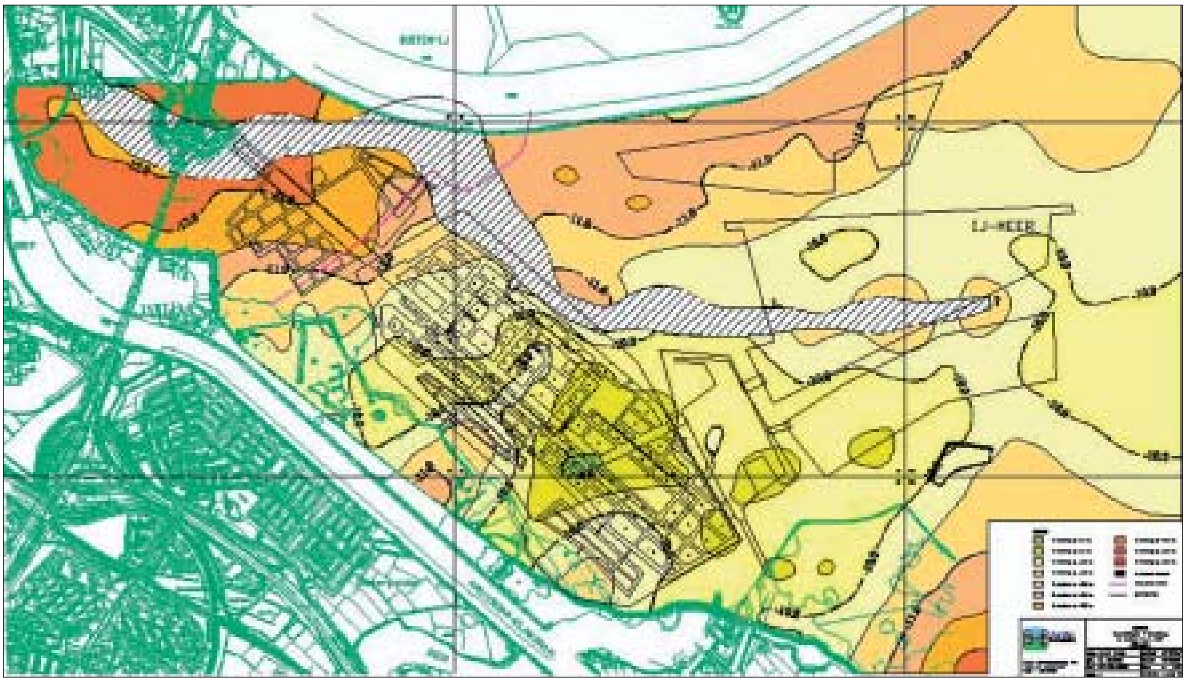
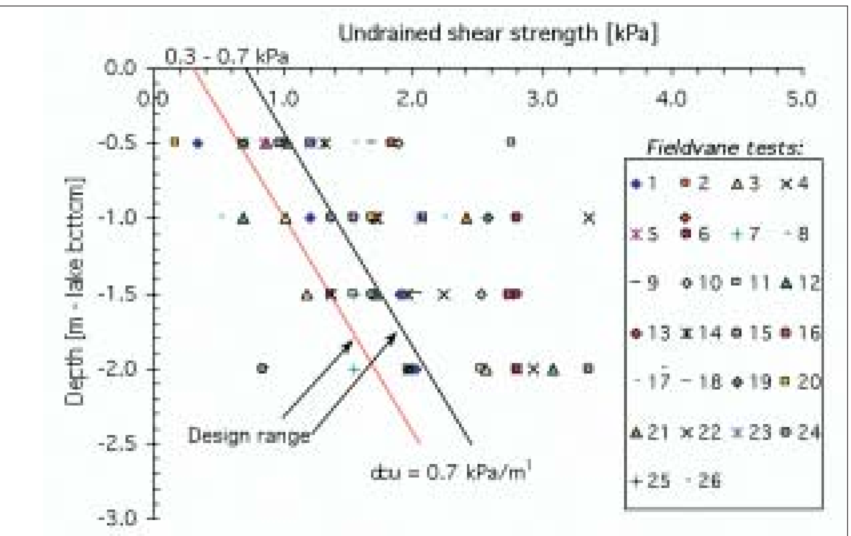


*Figure 11. Isohypsenchart of elevation top of Pleistocene sand.*

plays a dominant role. The undrained shear strength of this layer is measured with in-situ field-vane and laboratory testing. The undrained shear strength values versus depth, resulting from corrected field-vane values, are presented in Figure 12.

The large scatter in undrained shear strength values is a direct result of the variability of the geological profile in the area. This variability over the area is even better indicated with the contour map of the undrained shear strength at a depth of 0.5 metre below bottom, as presented in Figure 13. At the transition with the stiffer Holocene layers, there is a sudden increase in undrained shear strength to 4–5 kilo-Pascal.

*Figure 12. Undrained shear strength versus depth.*




The young Holocene clay is high plasticity clay as shown in the plasticity chart in Figure 14. In Figure 15, the Atterberg limits are plotted versus elevation, showing reasonably constant values with depth. The natural water content in the young Holocene clay layer is often slightly higher than the liquid limit. In Table I a summary of some characteristic soil parameters of the young Holocene clay layer is presented.

**Full-scale pilot project**

Given the extreme subsoil conditions it was decided to construct a full-scale pilot test in order to reduce the risk by experimenting with a new reclamation technique and enabling the optimisation of the reclamation itself. The design values of the soil parameters were determined after evaluating the in-situ, laboratory and full-scale test results. Especially the reclamation technique, the application of geo-textile and vertical drain spacing and thus construction phasing was highly influenced by the results of the full-scale test.

The full-scale pilot project, constructed in 1994–1995 in the IJmeer, is an island with a width of 100 metre and a length of 300 metre and formed part of the future IJburg area.

The island was divided into three sections of around 100 x 100 metre each to test the rate of consolidation, magnitude of settlements and soil structure interaction of reinforced soil. For this purpose a reference section without vertical drains (prefabricated strip drains) was used and in two sections vertical drains were installed in a triangular grid with distances of 1.0 and 1.5 metre, respectively.

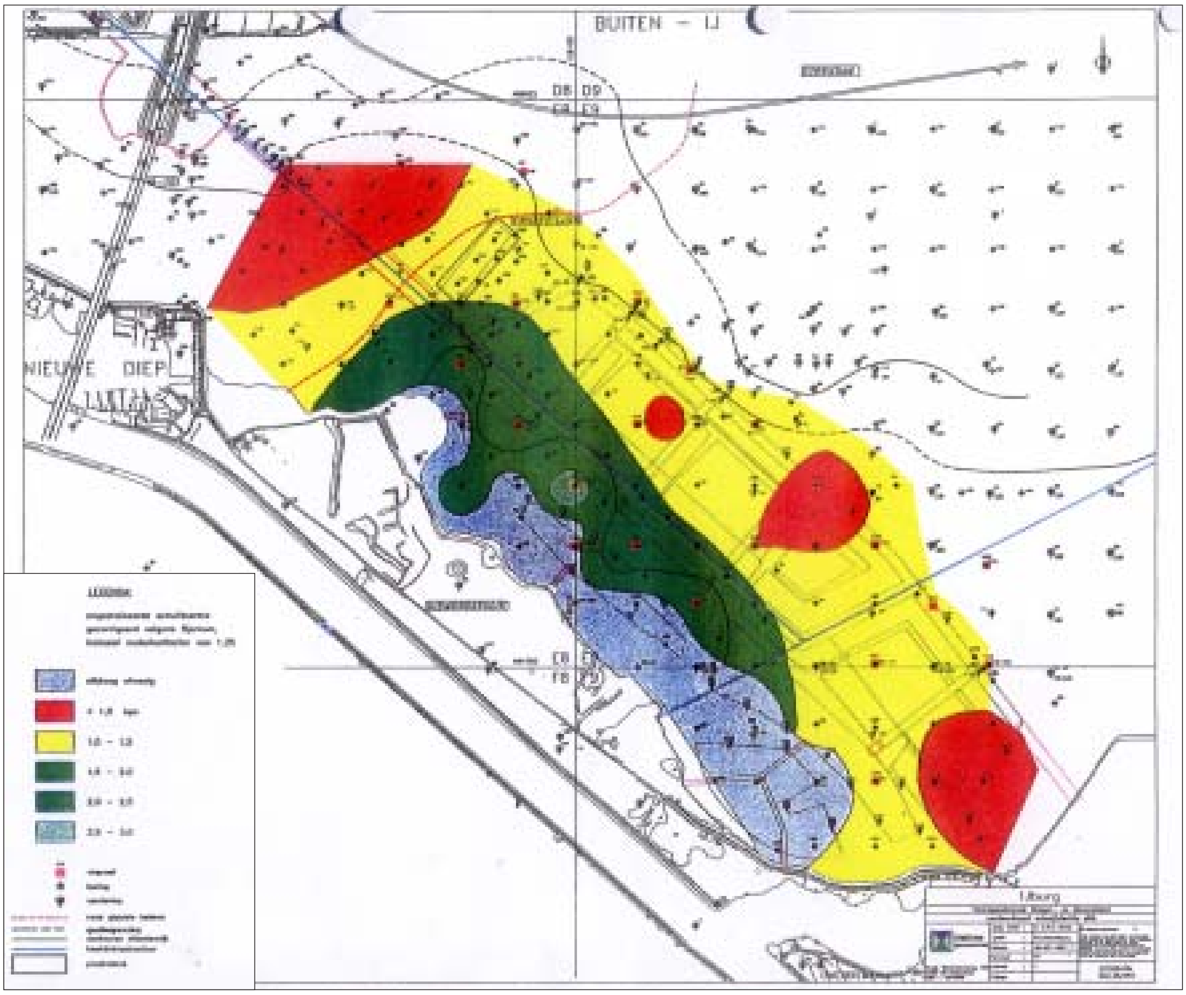



*Figure 13. Contour map of the undrained shear strength (at depth 0.5 metre below bottom).*

Polyester geo-textile (PET 80/80 kN/m1) was placed on the bottom of the lake before the start of the reclamation with the spraying pontoon, to stabilise the island embankments during reclamation works. Strain gauges were attached to the geo-textile to enable measurement of stresses in the fabric.

In Figure16 the development of the strain during the construction process in the geo-textiles is presented. The sections with the vertical drains show a strain of only 2%, whereas the measured elongation in the reference section was 6%. An elongation of 6% corresponds with a horizontal displacement of about 1.0 metre. These horizontal displacements were indeed observed during the construction of the last stage, almost resulting in failure in that section.

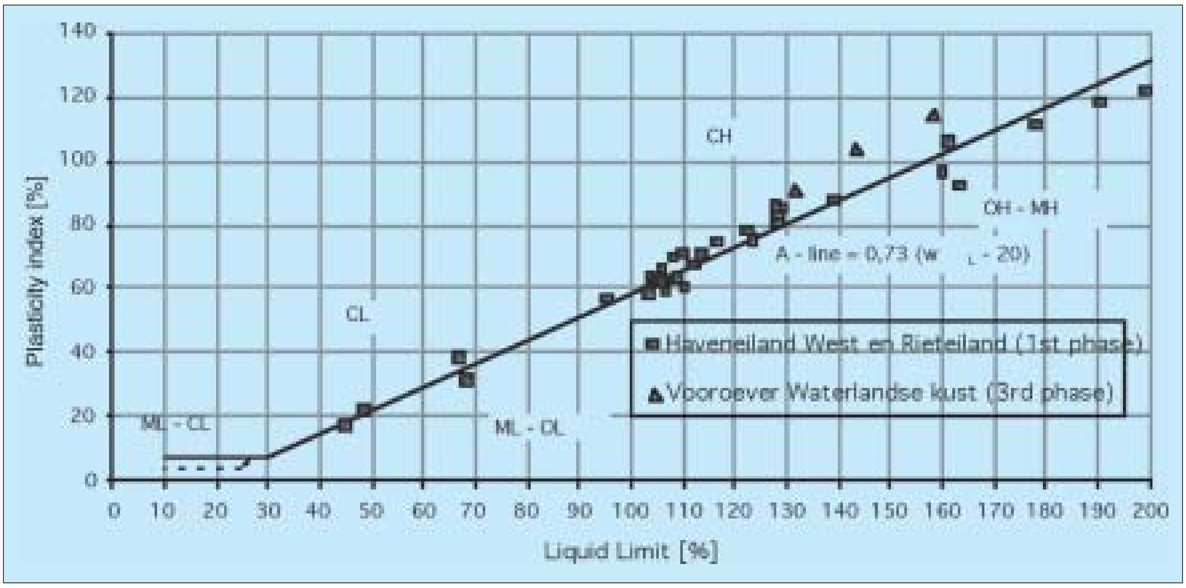
The function of the geo-textile in the reference section is mostly ensuring a clear transition layer between sand and the soft clay, and increasing of the internal stability of the sand in the slopes.

After completion of the reclamation of the pilot project an additional 10-metre-wide strip of sand was placed directly on the young Holocene clay layer by the spraying pontoon without the use of a geo-textile.

No soil disturbance was observed during the construction activities. Soil investigation with boreholes at that specific location showed a remarkably clear transition between the sand and the young Holocene clay layer. As a direct result of this discovery, geo-textiles were only used under the future dikes of

**Table I. Characteristic soil parameters of the young Holocene clay layer.**

| Description | Value | Description | Value |
|---|---|---|---|
| Wet unit weight [kN/m$^3$] | 12.7 | Natural water content [%] | >110 |
| Compression ratio CR [-] | 0.284 | Liquid limit [%] | 110 |
| Secondary compression coefficient | 0.0128 | Plastic limit [%] | 40 |
| Vertical consolidation coefficient [m$^2$/s] | 2 x10$^{-8}$ | Plasticity index [%] | 70 |
| Vertical permeability [m/s] | 1 x10$^{-9}$ | Lutum fraction (< 2 μm) [%] | 40–50 |



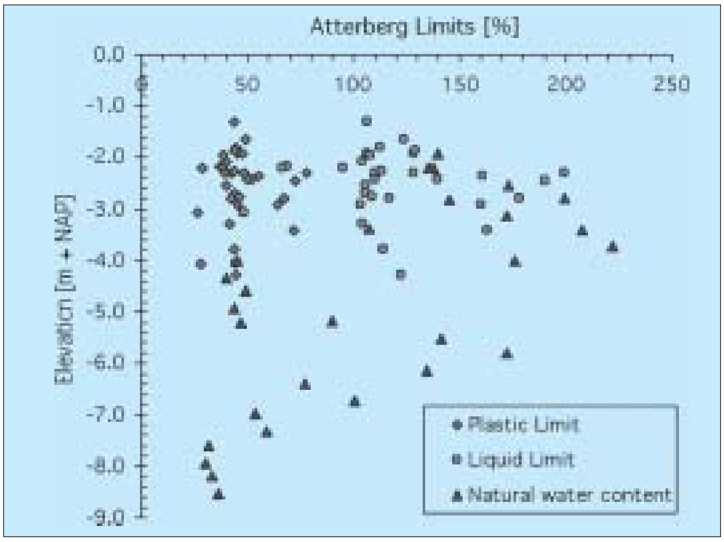



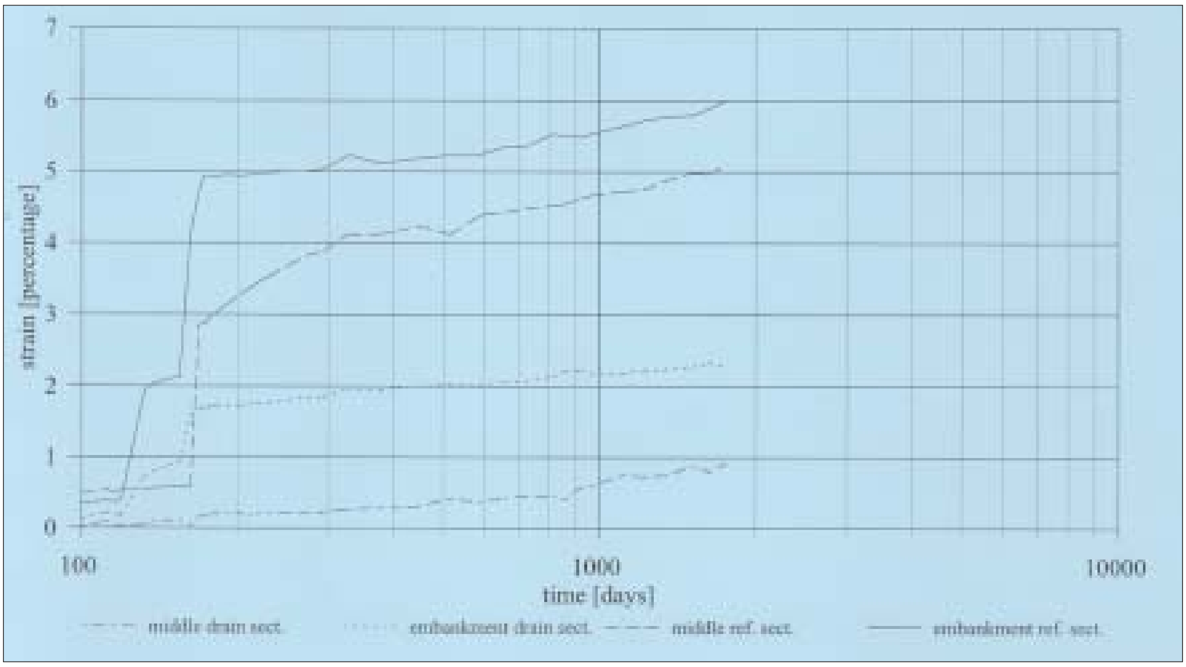

Figure 14. Plasticity chart: Haveneiland West and Rieteiland (1st Phase) and pre-bank of the Waterland coast (3rd Phase)

Figure 15. Left, Atterberg limits versus elevation.

the northwest side of IJburg. The function of these geo-textiles was reduction of the plastic shear strain during the first construction stages and in some cases improving the stability during the construction of the dikes and temporary surcharge.

The reclamation of the pilot project was completed in 6 months using a staged construction method. The first three layers, with an average thickness of 0.6 metre, were placed under water using a specially designed

Figure 16. Pilot project: development of strain in geo-textiles.



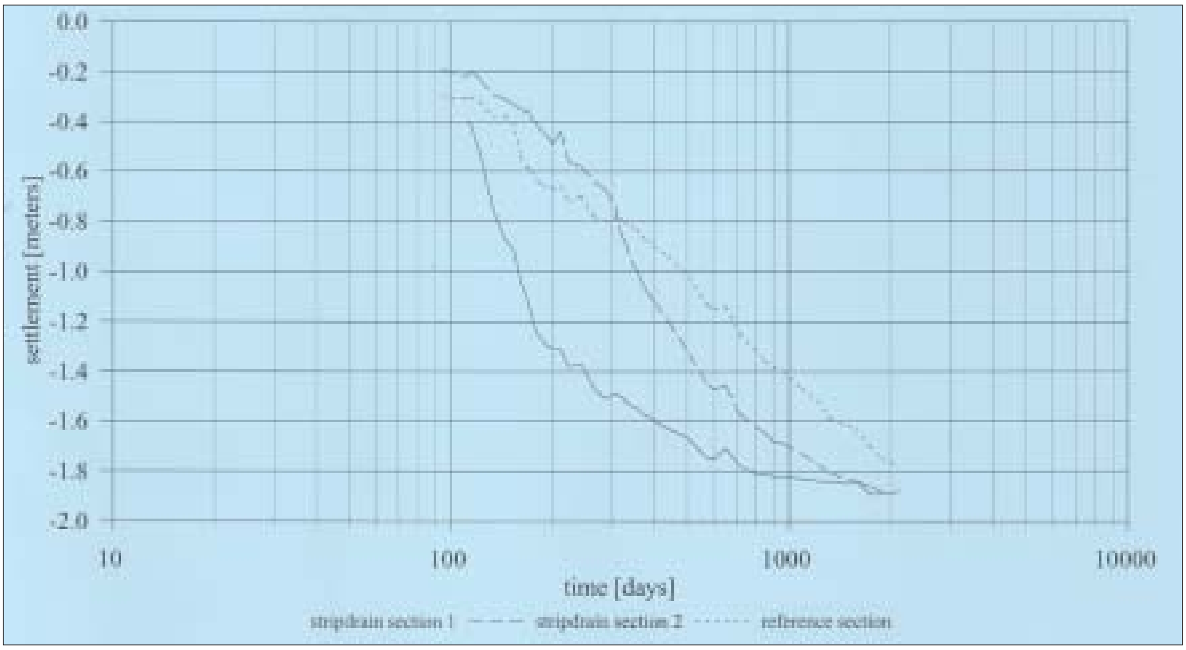



*Figure 17. Pilot project: measured settlements versus time.*

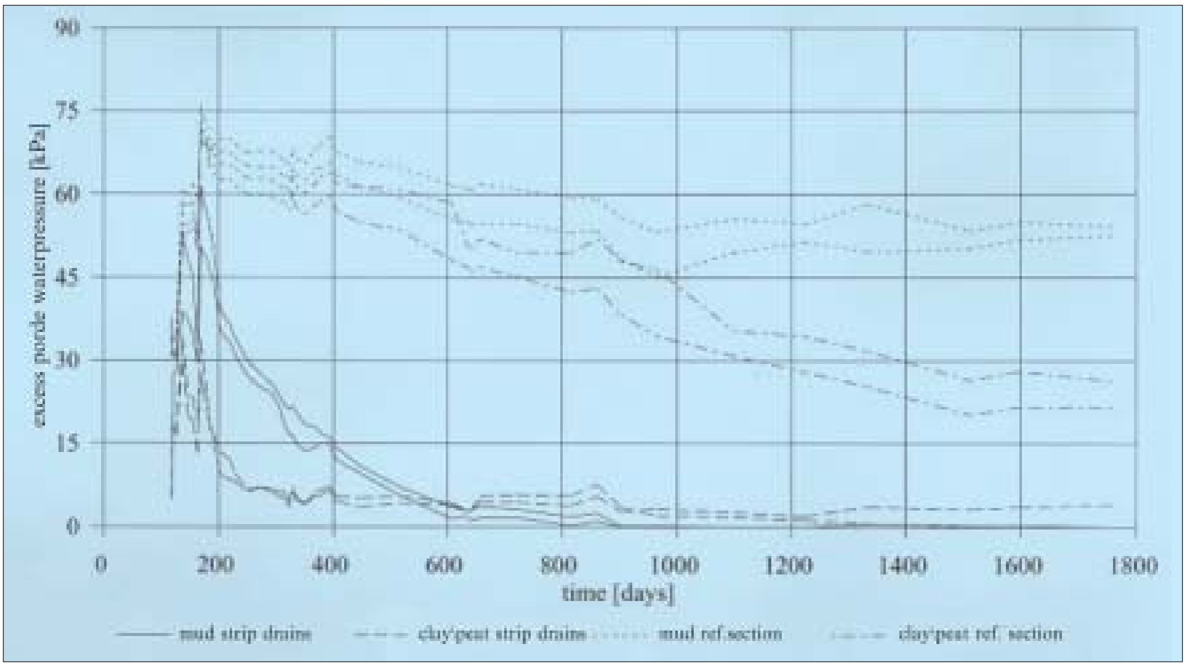
spraying pontoon. With this spraying pontoon a constant sand thickness can be placed on the lake bottom thus avoiding load differences, which can cause instability.

A conventional hydraulic placement technique was used for the reclamation between the watertable and the final height of 3 metres above NAP.

The total thickness of the sand layer is 5.2 metres and the corresponding predicted total settlement after 30 years was 2.3 metres. In Figure17 the measured settlements versus time are presented. The reference section without vertical drains is still not fully consolidated, while the other sections are fully consolidated and show secondary compression.
The total back-calculated settlements are approximately 0.3 metre less than expected, which is largely explained by the overestimation of the secondary compression of the young Holocene clay layer. Correction of the secondary compression parameter or change of model both resulted in accurate post-dictions.

The application of prefabricated strip drains resulted in an accelerated consolidation period for the young

*Figure 18. Pilot project: Excess pore water pressures versus time.*



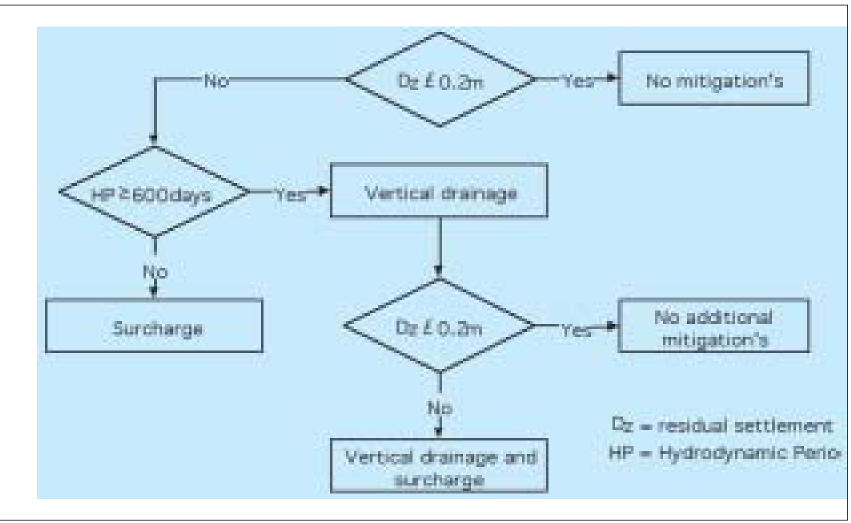



*Figure 19. Decision-tree for improving engineering properties.*

Holocene clay layer and the Holocene layers of 600 and 200 days, respectively. The consolidation period in the reference section without vertical drains is approximately a factor 10 longer. The large strains and organic content did not significantly affect the functioning of the drains. The dissipation of the excess pore water pressures for the various sections of the pilot project is presented in Figure 18.

The speed of consolidation of a multi-layer soil stratum usually can be modeled using one equivalent consolidation coefficient for all the layers. The deviation of the consolidation behavior of the young Holocene clay layer proved to be too large compared to the underlying layers, resulting in an overestimation of the rate of settlements. Very good agreement in post-dictions were achieved using Onoue's principle [ref. 4], where the rate of consolidation is calculated separately for each soil layer. This method is used for the design and back-calculation of the latter construction phases of IJburg.

**Geo-technical aspects of the reclamation design**

The following boundary conditions were applied for the reclamation design of IJburg:

- No removal of young Holocene clay layer. Although removal of this layer would result in a reduction of settlements and stability problems, this option was not chosen given the large required disposal volume.
- Hydrodynamic period. The hydrodynamic period for the infra-structural zones should be less than 300 days in order to guarantee the in time functioning of public transport. The hydrodynamic period for all other areas of the island should be less than 600 days.
- Maximum residual settlements of 0.2 metre. The residual settlements for the non-construction areas were calculated for a life cycle of 30 years. Pile foundations are used for the houses and apartment buildings. The piles are founded on the first or the second Pleistocene sand layer depending on the maximum allowed residual and differential settlements of the buildings.
- Island elevation. The future elevation of the island is 1.0 metre above NAP and 1.8–2.4 metres above NAP for the dikes and infrastructure.

The stability, settlements, required sand thickness and hydrodynamic period are calculated for each location of the island. Depending on the specific subsoil condition vertical drains, surcharge or combinations were prescribed, thus improving engineering properties. The decision tree whether or not soil improving techniques are required is presented in Figure 19.

**Geo-technical design optimisations and monitoring during execution of the first phase**

The land reclamation of IJburg consists of two construction phases. After completion of both phases, the area should be transformed in an archipelago. In order to prevent large stability and settlement problems, the north side of the archipelago was shifted slightly in a southerly direction, away from the tidal channel.

The main geo-technical problem of IJburg is slope stability, caused by the extreme low shear strength of the young Holocene clay layer. The optimum geo-technical design is obtained by minimisation of the slope length.

The chosen construction method consists of the construction of sand "pancakes" with a spraying pontoon, covering a part of the footprint of the archipelago (Figure 20). After consolidation and building of the houses and apartments, canals are excavated thus making smaller islands. The stability of the slopes is significantly improved because of the increase in undrained shear strength of the subsoil by the consolidation process. The excavated sand and the sand from surcharges are reused in a next construction phase.

Similar to the pilot project, the underwater layers are placed with the computer-controlled spraying pontoon. The first sand-layer thickness is typically 0.5 metre ± 0.05 metre with front and side slopes of 1:5 and a back slope of 1:10. The width of each sand blanket placed by the spraying pontoon is approximately 12 metres. The different blankets, placed side by side, form the sand pancake.

The geo-technical success of the project depends on the accuracy of placement of this first sand layer. An unforeseen deviation in end-slope and layer thickness can have serious consequences in following construction stages. The following layers typically have

*Figure 20. The construction of "sand pancakes" by a spraying pontoon. The first sand layer was typically not more than 50 centimetres. The following layers have a thickness of between 0.6-0.8 metres.*

a thickness of around 0.6–0.8 metres. The underwater slopes vary, depending on the subsoil conditions, between 1:4 and 1:10, resulting in a low-pressure gradient. The slopes above the watertable vary between 1:4 and 1:8.

The sand thickness varies over the islands, depending on functional requirements and subsoil conditions. Maximum sand thickness up to 9–10 metres was placed in the dikes with 2–3 metres temporary surcharge.

As previously mentioned, a light geo-textile (PET 80/80 kN/m[1]) is only used on the bottom layer under the dikes to reduce plastic shear strains and to increase the internal stability of the sand on top. The location of this geo-textile was changed, during the realisation of the first land reclamation phase, from the top of the young Holocene clay layer to the top of the first sand layer (below water level). This resulted in better friction along the interface of the geo-textile and improved strain strength behaviour.

The excellent results with the spraying pontoon made it possible during the construction of Steigereiland to place the heavy PET 400 geo-textile above water instead of underwater. At the northwest side of this island, which has the weakest subsoil of IJburg, 10 metres of sand had to be placed in the dike. The application of a strong geo-textile (PET 400 / 50 kN/m[1]) was required to ensure a stable dike construction. This geo-textile was placed after installation of the vertical drains at an elevation of around 0.5 metre above NAP (see Figure 10). Placement of the textile after installation of the vertical drains meant that the textile was not perforated and therefore not weakened by the vertical drains. Such perforation of the geo-textile would have reduced the strength of the geo-textile by at least 50%.

During the land reclamation of IJburg various monitoring instruments were installed. Some 170 settlements plates, 92 piezometers and 10 inclinometers were installed. Further, at 13 locations differential settlement measurement were performed. The resulting data was processed and calibrations and back-calculations were performed.

For the land reclamation process the stability calculations played a dominant role. The stability was initially calculated with the slip surface programme Slope/w (version 3) from Geoslope [ref. 2]. During the commencement of the works Finite Element Model (FEM) calculations with the computer code PLAXIS [ref.5] were performed. These calibrated calculations enabled prediction of displacements, plastic behaviour and shear-induced excess pore water pressures.

The shape of the failure mechanism is best validated with PLAXIS. The resulting safety factor can be verified with Slope/w for a predefined failure mechanism. The strength improvement as a result of the consolidation process is modelled according to Ladd [ref. 3], using the fully undrained analysis with strength increase. The results in the safety factor of both models were quite comparable.

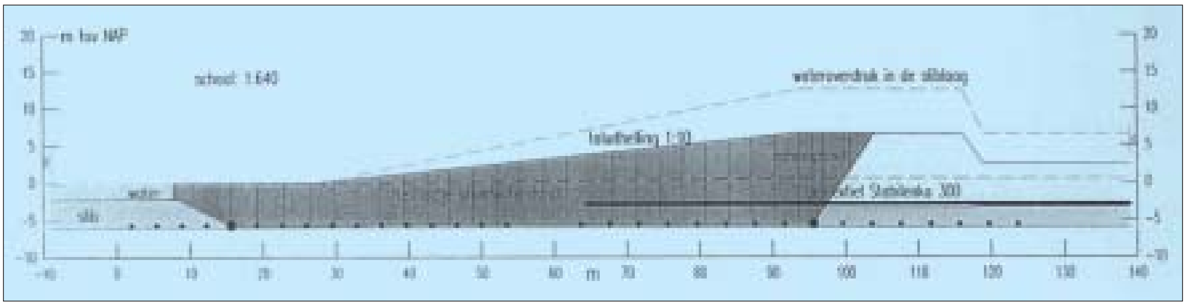
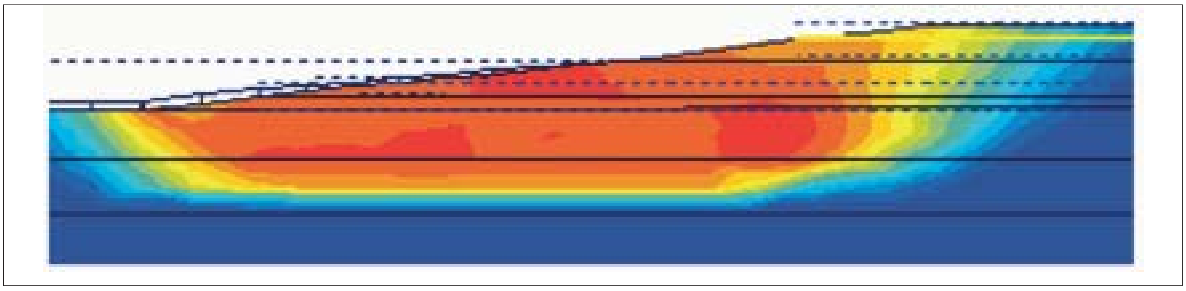


*Figure 21. Steigereiland (Bastion): Results stability calculation Slope/w.*

*Figure 22. Steigereiland (Bastion): Results stability calculation PLAXIS.*



Until the installation of the vertical drains, the failure mechanism was mainly squeezing. The young Holocene clay layer squeezes over the firmer deeper layers. After consolidation and resulting strength improvement the failure mechanism transformed to a transition mechanism combining both circular and horizontal sliding. In Figure 21 and Figure 22 the results of the stability calculations from, respectively, Slope/w and PLAXIS are presented. The settlement and piezometer readings versus time of the same location are presented in Figure 23.

Some of the so-called optimisations were a direct or indirect result of a significant deviation of the design. Although always very unwelcome, slope failures are always a good opportunity to benchmark to original boundary conditions and calculation assumptions. In the first reclamation phase, two failures occurred, and

*Figure 23. Bastion Steigereiland: Settlements and piezometer readings versus time (R23).*

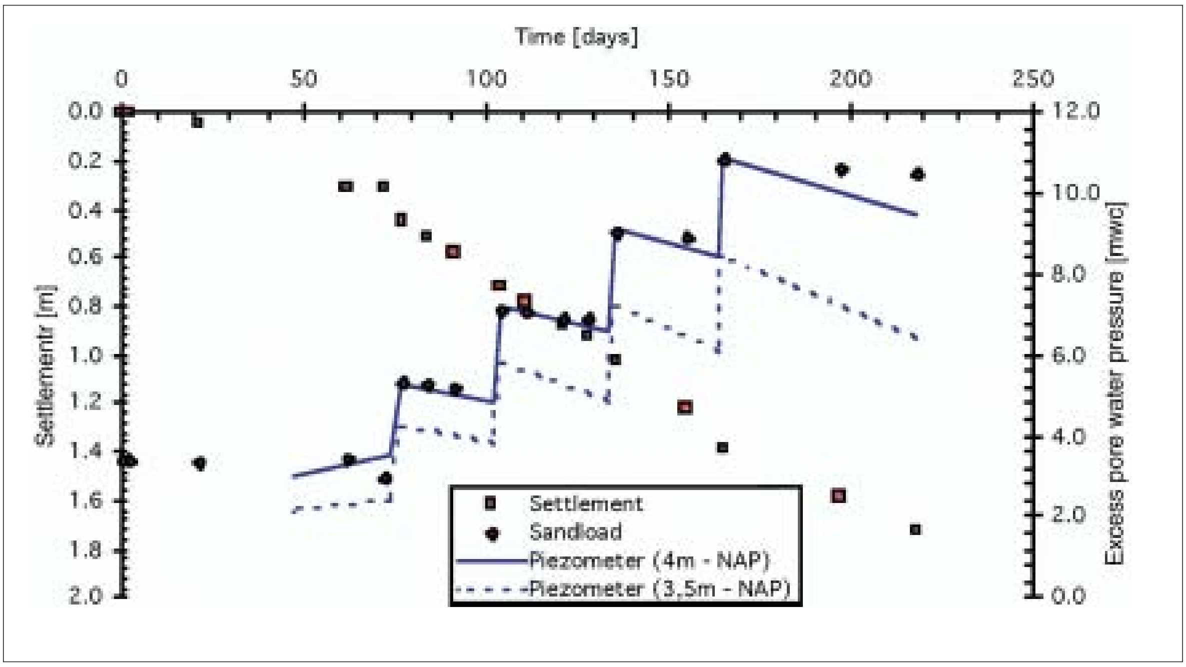


*Figure 24. Slide at northwest corner of Haveneiland (24 November 2000).*

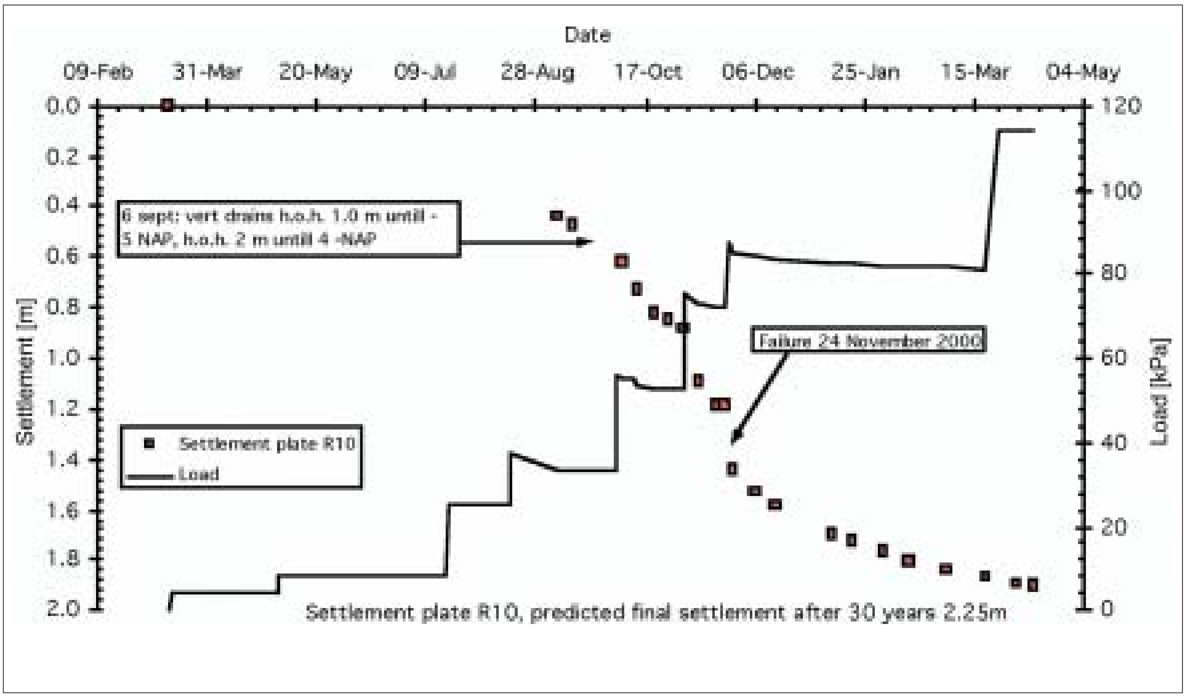
fortunately much was learned from them. One of the failures occurred at the northwest side of Haveneiland as a result of an overestimation of the strength improvement. The resulting photo of the failure and corresponding settlement versus time curve are presented in Figure 24 and Figure 25.

Since then no more failures have occurred, while the reclamation process goes faster by the effective use of intermediate consolidation periods. Thanks to the lessons learned, the contractor Combinatie IJburg was capable of speeding up the reclamation process even more.

The full-scale pilot project was very successful for the prediction of both settlement magnitude and rate of consolidation for the following reclamation phases. In general, only marginal deviations could be observed.

The variability of the subsoil was at some locations cause for a deviation in settlement magnitude and rate of consolidation. In both separate cases the Pleistocene estuarine trench with accumulated young Holocene sediments was to blame. The soil investigation campaign with an intermediate standard grid-distance of 200 metres proved too large to locate these small 30–50-metre-wide trenches.

*Figure 25. Haveneiland West: Settlements versus time.*



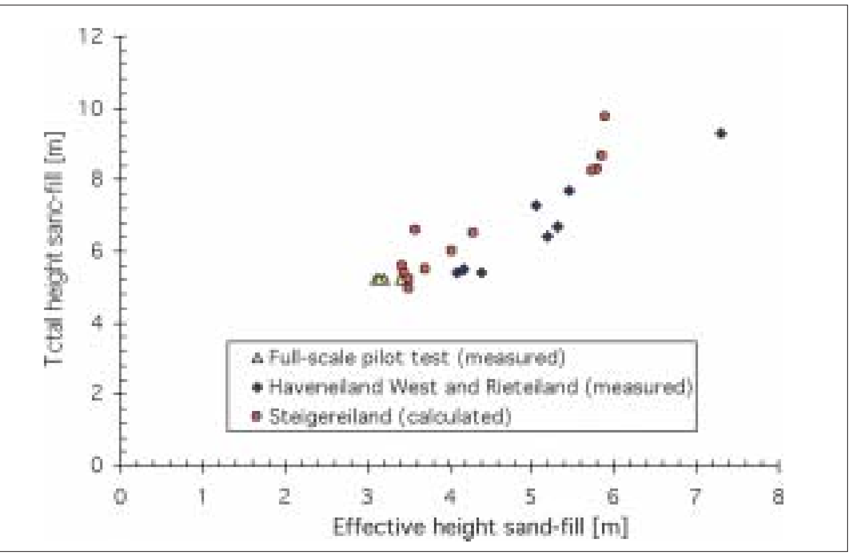



*Figure 26. Effective versus total height sand fill.*

Back-calculations proved that the residual settlements were 0.35 metre larger within the same time frame, resulting in a possible required advanced maintenance of the infrastructure on that location. The rate of consolidation dominated by the horizontal consolidation coefficient on the other location was twenty times higher than conservatively predicted, caused by both heterogeneity and horizontal layering of peat.

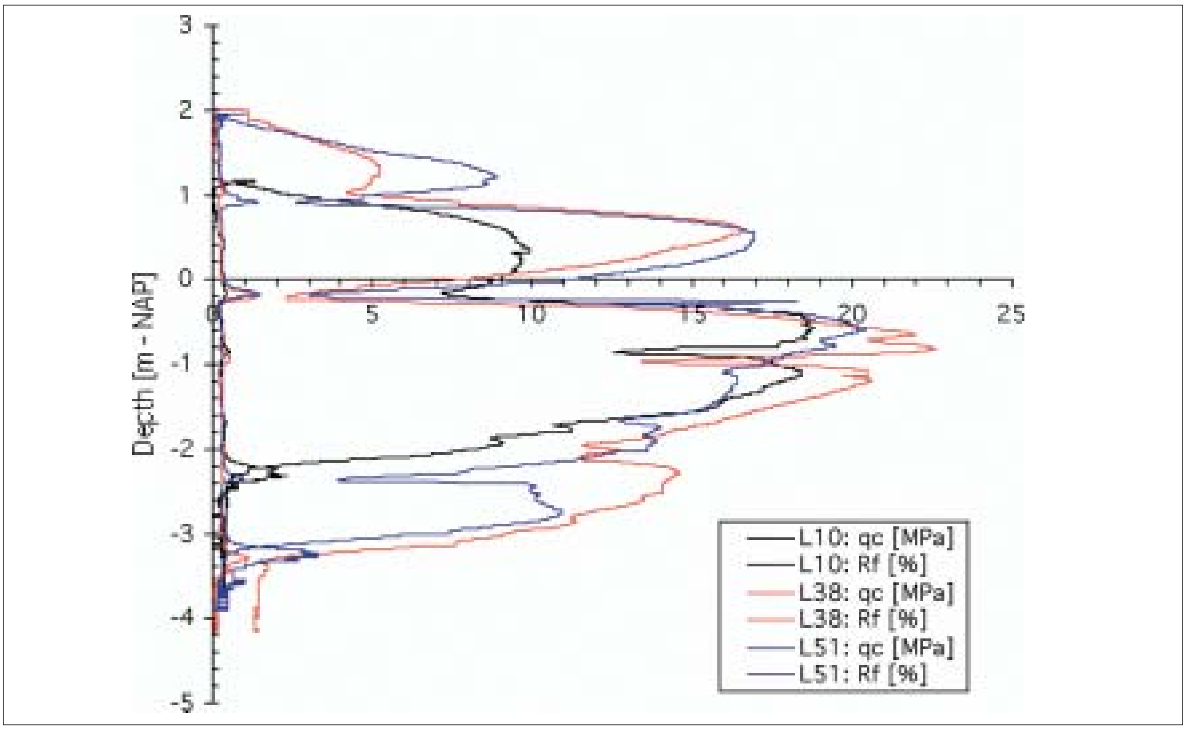
In Figure 26 the effective versus the total height of the sand fill from three different land reclamation phases are presented. The ratio between both varies between 1.4–1.7, which can be related to the specific subsoil conditions in the IJburg area.

The cone penetration resistance versus depth from random locations is presented in Figure 27. The quality of the placed sand fill is excellent. Besides the placement method of the spraying pontoon underwater and conventional filling with pipelines and bulldozers above the watertable, no additional compaction was performed.

## Sand Extraction and Overburden Removal by "Clay Relocation" Method

The quantity of sand needed for reclamation was present in the lake Markermeer, an area relatively close to the reclamation site. In Figure 4, the location can be seen. The sand however was covered by an 8-metre-thick layer of soft to firm clay and peat. The dredging of the sand and removal of clay had to be executed in such a way that upon completion, an 8-metre-deep and around 100-metre-wide shipping lane would be created stretching from the city of Amsterdam to the city of Lemmer. This would result in a large benefit because the existing shipping lane was only 4 metres deep. The existing overburden of clay however created a problem, because no temporary storage areas were available. The problem was solved by dividing the borrow area into relatively small sections for excavation of average 500 metres length per section (Figure 28).

*Figure 27. Cone penetration resistance versus depth.*



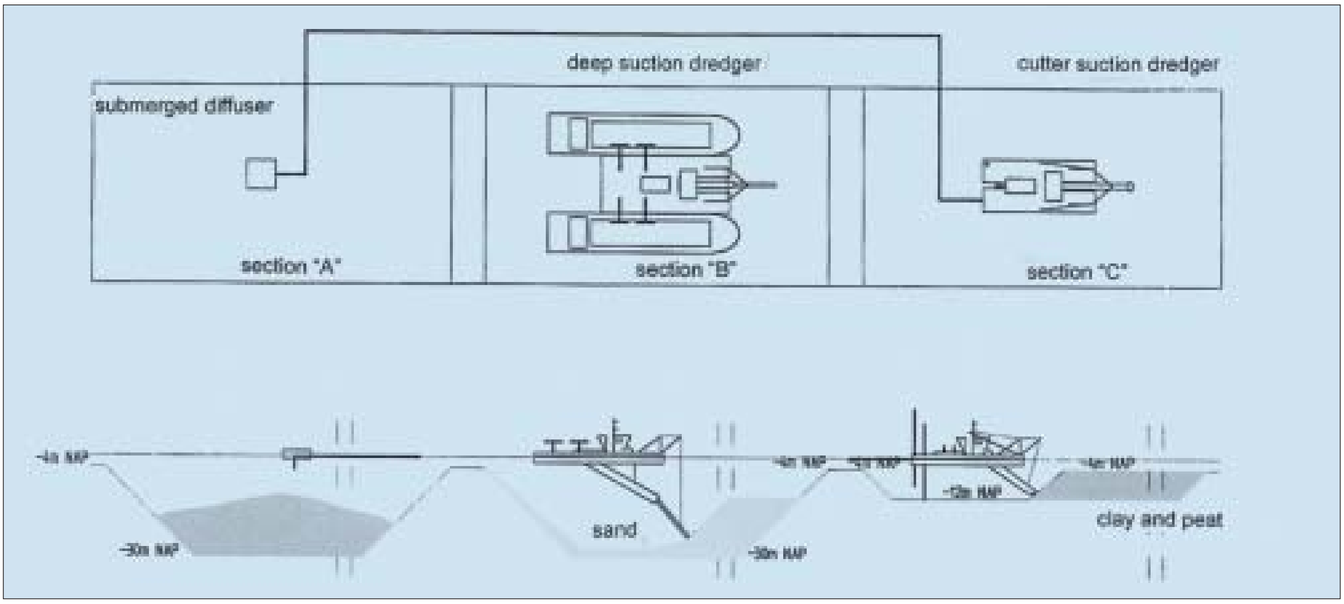



*Figure 28. Diagram: top and side views showing the "train of dredging activities" in order to excavate the sand and relocate the overburden of clay. This method of dredging avoided the need for large temporary storage areas for the volumes of clay to be dredged. In the photograph (taken on 27 March 2002) the deep suction dredger Faunus and the cutter suction dredger Aegir can be distinguished.*

As soon as the sand in section A is excavated, the deep suction dredger moves to section B to continue with the sand excavation. From that moment a cutter suction dredger starts to remove the clay overburden in section C and pumps it to the already emptied section A. The clay is pumped through a pipeline to a pontoon with a submerged diffuser installed (environmental requirement), which gradually spreads the clay in a controlled manner on the bottom of section A. In this way section A is filled to a depth of 8 metres below water level, this being the required depth for the shipping lane in the future. To prevent clay flowing back into section B and thus disturbing the sand excavation, dams of 20 metres wide were left in place by the deep suction dredger when dredging the sand. In Figure 28 a schematic drawing shows this so-called "clay relocation method" and the photograph shows the dredging ships actually at work using it.

*Figure 29. Computer-controlled spray pontoon "1208" for reclaiming sand in thin layers. The pontoon can work in very shallow waters. The sand-water mixture escapes the pontoon over a 12-metre-wide chute. The density and velocity of the mixture is measured on board. A computer calculates as well as controls the speed of the winches in order to reclaim with any desired constant layer thickness. Photograph taken on 29 April 1999.*

Clearly a proper and accurate sand-clay balance, based on an extensive soil investigation by means of a large number of borings, was of crucial importance. The calculation of the sand-clay balance determined the length of each section and the depth of sand excavation. After completing each section the balance had to be reviewed and adjusted, based on the actual volumes dredged and echo soundings taken. Constant bathymetric survey activity was necessary here.

To minimise sedimentation into a section (especially in the winter season) the clay removal had to be executed shortly before the sand excavation started. In such a way the time span that a sand surface was subject to sedimentation was minimised. This required careful planning and, to minimise mobilisation activities, a proper choice of the capacity of each dredger used had to be made. When these guideines are observed, a constant "train" of dredgers and pipelines can work continuously and simultaneously, without excessive idle time and mobilisation costs and, most important of all, the clay does not have to be stored temporarily.

## Spraying Sand in Thin Layers with Constant Thickness

To prevent instabilities of the soft subsoil and to avoid installation of large surfaces of costly geo-textiles on top of the existing subsoil, the design prescribed a controlled method of reclamation in thin layers together with consolidation periods of 4 weeks between each layer of reclamation.

The technique of the computer-controlled spray pontoon named "1208" enabled the contractor to reclaim sand in layers with a thickness of 20 centimetres or more, while at the same time maintaining high accuracy. This pontoon proved to be successful in meeting all the requirements of the contract. However when such thin layers of sand underwater are required with a high accuracy in both vertical and horizontal direction several problems arise. Some of these are described hereunder.

**Working in shallow water**

Reclaiming layer after layer gradually reduces the available water depth. Ultimately, during spraying of the last layer, a maximum water depth of only 60 centimetres remains. Together with an unfavorable direction of the wind this depth can further be reduced. Therefore two spray pontoons with minimum draft were used. One of them, spray pontoon "1208", can be seen in Figure 29.

Equally important, floating pipelines with minimum draft had to be used. Instead of conventional rubber type flexible floaters, in most cases steel pipelines (light weight) installed on large oversized pontoons were used. This enabled the contractor to work in extremely shallow areas. All auxiliary equipment, for instance the "Multicat", had to be able to work at these same

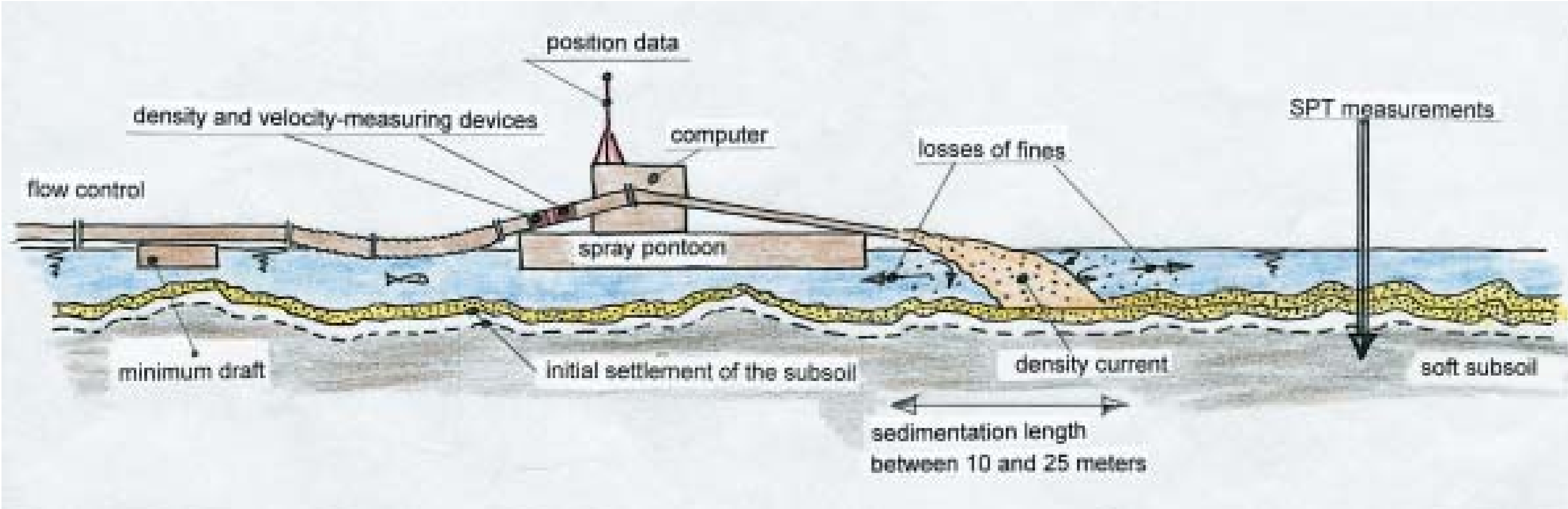



*Figure 30. Schematic drawing of the spray pontoon "1208" and the process features of spraying sand as described in this article.*

restricted water depths. Despite this shallow draft equipment, delays could be encountered because of grounded equipment or pipelines stuck on a sand shoal.

**Anchoring the spray pontoon and pipelines**

Reclaiming thin layers meant that the spray pontoon had to move relatively fast, which results in very frequent anchor handling. Anchoring in soft subsoil and shallow water limits the choice of anchor types that can be used. In order to find the best solution for the problem, various anchor types and ways of anchor handling were tried out in the beginning of the project.

With regard to the production process, the shifting and handling of the anchors had to take place with a minimum of delay time to the reclamation process. To reach this, an extremely close, hourly, coordination with the crew of the pontoon was maintained and proved to be indispensable. Working with an experienced crew was of crucial importance here.

**Moving the pontoon**

With an exactly constant production level the spray pontoon would have to move at a constant speed in order to achieve a constant layer thickness. However, the production of the barge unloading dredger will always vary because of changing of the barges every 30 minutes, variations in sand quality, pipeline obstructions, technical problems and other process irregularities. When a constant layer thickness is required the speed of the spray pontoon therefore has to be adjusted in line with the variations of the production level.

Hereto the actual production level was continuously measured through density- and velocity-measuring devices on board the spray pontoon. Together with actually measured data defining the positions of the pontoon and its six anchors, as well as input data of the required layer thickness, the on board installed computer calculated the necessary speed of the six anchor winches. The computer-controlled winches would then immediately and automatically move the pontoon along a straight line with such velocity that the constant pre-defined layer thickness was reclaimed.

The computer calculations had to be adjusted for the effects of the sand-water density current underwater. The sedimentation length of this current varied between 10 and 25 metres depending on the depth of the water and the grain size of the sand. The grain size of the sand varied between D50 = 150 micron and 250 micron.

Also adjustments had to be made for the losses of fines during reclamation. These losses depend directly on the quality of the sand (especially the content of fines within the sand) and the current velocity of the surrounding waters. Losses owing to fines varied from two percent to fifteen percent. These losses (if not corrected for) would result in reduced and varying layer thickness and thus jeopardise the stability of the subsoil.

Accuracy of the realised layer thickness was increased by maintaining a production level as constant as possible, through the use of a flow control on board the dredger *Sliedrecht 26*.

Finally, when checking the realised layer thickness by means of comparing bathymetric surveys before and after reclaiming, one has to adjust for the initial settlement of the subsoil. This settlement varied from 1 to 15 centimetres, depending on the location, and occurred within one or two days. Soil borings or SPT measurements were used to eliminate this inaccuracy resulting from initial settlement. Figure 30 shows some of the aspects mentioned here.

### Reducing Dredging Delays Through Careful Planning

By careful planning it has been possible to reduce delays and idle time during the dredging process to a minimum, finally resulting in an earlier completion date. Hereto the total reclamation area was divided in five smaller areas and the sequence in reclaiming these smaller areas was carefully chosen. The area with the least technical restrictions was reserved as much as possible for "emergency" situations and for the last four weeks of reclamation activities. In the end this area was filled for 95 percent during "emergency" situations.

At least two outlets, and most of the time three outlets, were kept available for reclaiming sand. Whenever a certain reclaimed layer had to consolidate or anchor handling took place other outlets could be used. Moreover during wind from the southwest direction the level of the water reduced considerably and therefore the area was not accessible for the spray pontoon and equipment, in which case another outlet had to be used.

Delivery dates of geo-textile suppliers and milestones for installation of vertical drains by a subcontractor were kept extremely tight, because these activities would interfere with reclamation activities on the same area. As much as possible these subcontractor activities were planned in a three-weekly period of summer leave for the dredging crews and process.

## Conclusions

The use of the fully computer-controlled spraying pontoon enables controlled land reclamation in an area with extreme soft subsoil conditions. The geo-technical success of the project depends on the accuracy of placement of this first sand layer. An unforeseen deviation in side, end-slope and layer thickness can have serious consequences in following construction stages.

The application of a geo-textile in the underwater layers could be omitted because of the high accuracy of sand placement with the spraying pontoon and the observed clear transition between the sand and the young Holocene clay layer. The plastic shear strain under the slopes can be further reduced by application of shallow slopes.

The combination of a full-scale pilot test, an extensive monitoring campaign and online validation and back-calculation results in a safer construction method and can result in various optimisations. The use of Finite Element Models in combination with validation tools result in more accurate predictions and a better understanding of soil structure behavior in complex situations.

By careful planning it has been possible to reduce delays and idle time during the dredging process to a minimum, finally resulting in an earlier completion date.

At the sand borrow area a large amount of clay had to be removed. By applying the "clay relocation method", a proper planning and a sand clay balance, a shipping lane was created and it was not necessary to construct temporary clay storage areas.

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