Proceedings of the XVI ECSMGE
Geotechnical Engineering for Infrastructure and Development
ISBN 978-0-7277-6067-8

doi:10.1680/ecsmge.60678

Design, construction and monitoring of 18m thick embankment on top of very soft peat using BeauDrain vacuum consolidation

Dimensionnement, construction et suivi d'un talus de 18m de hauteur sur une tourbe très molle avec un système de consolidation accélérée Beaudrain

J.W. Dijkstra*[1]

[1] *Cofra B.V., Amsterdam, The Netherlands*
* Corresponding Author

ABSTRACT BeauDrain vacuum consolidation has been used for the accelerated consolidation of a 7.5m thick very soft soil layer consisting of peat and clay underneath a new 10.5m high embankment near Amsterdam, the Netherlands. The requirement for the consolidation was a strict 20cm residual settlement over 30 years after construction. The tight construction schedule of the project led to filling rates of up to 0.75m of sand per week. During weekly meetings between the main contractor, the engineer of the client and the specialists of Cofra, the filling rate was evaluated using up to date monitoring data. This led to the safe construction of the maximum 18m thick preloading embankment in a staggering 8 months between September 2011 and April 2012. Due to unforeseen soil replacement sections, within the area to be consolidated, and the very soft peat, which caused major problems for the contractor to construct the working platform, the design was altered during the installation phase. In the altered design the BeauDrain system was combined with BeauDrain-S and Prefabricated Vertical Drains to prevent air leakage and pumping of water from the soil replacement of the neighboring highway. The embankment was handed over to the client within 10 to 12 months after the start of the pumps with settlements of up to 4 meters. This article presents the design, the solutions chosen and monitoring data obtained during the consolidation phase of the project.

RÉSUMÉ Le système Beaudrain a été utilisé pour accélérer la consolidation d'une tourbe et argile très molle de 7.5m d'épaisseur sous un talus de 10.5m de hauteur près d'Amsterdam, Pays Bas. Les conditions requises de tassement étaient de maximum 20cm sur une période de 30 ans après la fin de la construction. Le temps de construction limite amena à placer des couches de 0.75m de sable par semaine. En fonction des résultats de mesures du talus, le planning de construction a été adapte durant les réunions entre l'entreprise de construction, le représentant du client et le spécialiste de Cofra. Ceci permit la construction contrôlée du talus sur une hauteur allant jusqu'à 18m pendant une période de 8 mois entre septembre 2011 et avril 2012. Du fait de problèmes de remplacement de sol dans la zone de consolidation et de la faible résistance de la tourbe qui causa des problèmes majeur pour construire la plate-forme de travail, le dimensionnement a été modifié pendant la phase d'installation. Dans la nouvelle version du dimensionnement, un système Beaudrain combine avec une système Beaudrain-S et des drains verticaux pour empêcher les fuites d'air et le pompage d'eau dans les fondation du talus supportant l'autoroute adjacente. Le talus fut livre au client 10 a 12 mois après le début du pompage avec des tassements allant jusqu'à 4m. Cet article présente le dimensionnement, les solutions choisies et les résultats de mesures effectuées durant la phase de consolidation

1 INTRODUCTION

The new reclamation areas near Amsterdam, called IJburg, were, until recently, only connected to the surrounding main infrastructure through the so-called western access route. In order to accommodate for the increasing traffic due to the continuous expansion of the population, the project OOIJ, Dutch abbreviation for Eastern Access IJburg, was initiated. The project involved the development of an eastern access to the Islands and included the construction of a 150m single span bridge over the Amsterdam-Rhine channel and a connection to the highways A1 and A9. (See Figure 1 for the location of the project).

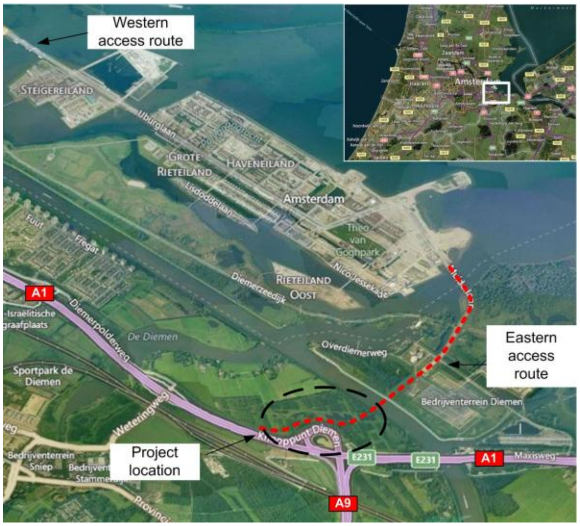

Figure 1. Location of the project in black oval (images modified from www.bing.com/maps , June 2014).

The maximum 10.5m high southern embankment, see Figure 2, connecting the bridge with the highway is located on a very soft, water logged, peat area. With the tight construction schedule and a low strength of the peat, a vacuum consolidation method was required to improve the 50.000m^2 of ground and safely construct and preload the embankments to residual settlements below 20cm over 30 years in eight months' time. This article gives the design and monitoring results of the embankment.

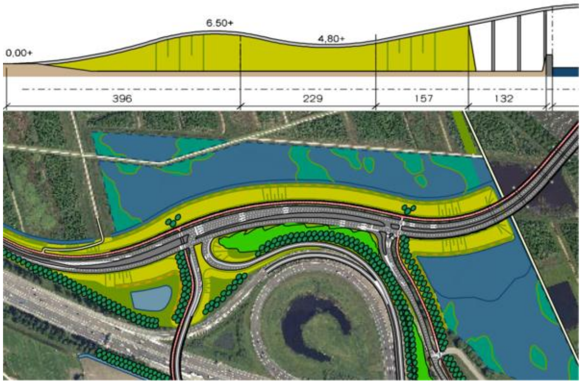

Figure 2. Embankment location and final surface levels of the embankment.

2 SITE INVESTIGATION DATA

The local soil profile at the site consists of a top layer of Holocene peat with a thickness between 4 to 4.5m overlying an organic Holocene clay layer, increasing in thickness towards the western project boundary. Below the clay layer, a thin basal Holocene peat layer is present on top of a thick Pleistocene sand layer. Within the thick sand body a highly overconsolidated clay layer exists, deposited during the last interglacial period. Table 1 presents the soil profile on both edges of the project. Figure 3 gives the spatial variation of the compressible Holocene layers.

Table 1. Soil profile at the project site

Soil layer	Top of layer most western section [m NAP]	Top of layer most eastern section [m NAP]
Peat	-1.52	-1.54
Clay_1	-5.71	-6.05
Peat	-9.31	-7.80
Pleistocene Sand	-9.71	-8.46
Eem clay_1	-13.71	-13.30
Eem clay_2	-14.50	-14.50
Eem clay_3	-17.00	-17.00
Pleistocene Sand	-21.50	-21.50

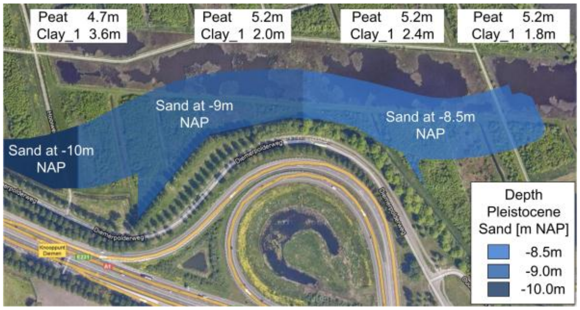

Figure 3. Spatial variation of the soil profile together with the total thickness of the peat and clay_1 layer assuming a surface level of -1.50m NAP.

The parameters of the soil layers were determined from laboratory data. The average consolidation parameters used in the design are given in Table 2. The design values of the strength parameters are given in Table 3.

Table 2. Design (average) values compressibility parameters

Soil layer	Unit weight [kN/m3]	CR* [-]	RR* [-]	C_α [-]	POP [kPa]	Cv [m^2/s]
Peat	10.0	0.513	0.079	0.029	10	5.0e-8
Clay_1	14.4	0.240	0.037	0.013	10	5.0e-8
Pl. Sand	20.0	0.022	0.003	0.000	-	1.0e-4
Eem clay_1	16.7	0.175	0.030	0.008	70	1.3e-6
Eem clay_2	18.3	0.084	0.011	0.004	45	6.9e-6
Eem clay_3	16.5	0.130	0.026	0.006	70	5.5e-6

* CR = Cc/1+e0, RR = Cr/1+e0

Table 3. Design values strength parameters

Soil layer	Unit weight [kN/m3]	C** [-]	Phi** [degres]
Peat	10.0	1.6	23.7
Clay_1	14.4	3.0	22.9
Pl. Sand	20.0	0	0.003
Eem clay_1	16.7	5.1	25.5
Eem clay_2	18.3	5.1	25.5
Eem clay_3	16.5	5.1	25.5

** Partial factor friction angle 1.15, cohesion 1.6

3 DESIGN

The software used to perform the settlement analysis is called HED-SET. This is an advanced validated in-house program with an Isotach type of settlement following the work of Yin et al. (1994) and the classical approach proposed by Terzaghi. The effect of the application of Prefabricated Vertical Drains (PVD) is modelled using the radial consolidation approaches proposed by Barron and Carillo. The software is capable to model, amongst others, staged loading-unloading construction, submerging, vacuum pressure and creep for 1D soil profiles. The performance of the model is further discussed in Dykstra et al. (2008).

The consolidation software was used in conjunction with stability software to calculate the potential measures to be taken to prevent undesired movement of the embankment and the safety factor against failure. It was concluded from the design that especially the first lifts were highly critical in terms of the stability. The required surcharging schedule, to complete the embankment and consolidation in twelve months, was only feasible with the use of vacuum consolidation as the vacuum pressure has a positive effect on the effective strength increase and speed of placement of the surcharge whilst not introducing an additional driving moment. Next to the vacuum pressure, a supporting berm of 10m wide and a 400kNm geotextile were required to reach the 20cm residual settlement within the given timeframe.

During the design, the drain spacing and lifting schedule were optimized over the length of the embankment. In the lower embankment sections a wider grid of 1.25m with a slower surcharging schedule of 0.40m per week was designed. For the higher embankment sections a lifting rate of 0.66m per week with a 1.0m drain spacing was designed.

The calculated sand thicknesses to be placed, including settlement compensation, were determined at values, depending on the height of the embankment, between 6 and 17 meter. After the consolidation period up to 3.5 meter of surcharge was required to be removed at the higher sections, against 0 meter at the lower sections. These high values of surcharge were required to reduce the creep of the peat till values below 20 cm in 30 years.

4 VACUUM SYSTEM

The vacuum system applied is installed using a machine with a specially designed plough to pull a horizontal collecting drain to a maximum depth of 2.5 m beneath the installation level (depending upon the thickness of the working platform and the groundwater level).

Figure 5. Installation equipment vacuum system

As part of the production process, this horizontal drain is automatically connected to the top of a vertical drain which is installed in the same installation process. In this same process a strip of membrane is installed on top of the horizontal drain to improve the sealing between the atmosphere and the drainage barrier. After the installation of a pre-determined number of drains, the blind section of the drain, led into the ground from the surface during the insertion of the plough, is connected to a vacuum pump. Figure 6 shows a graphical representation of the work method.

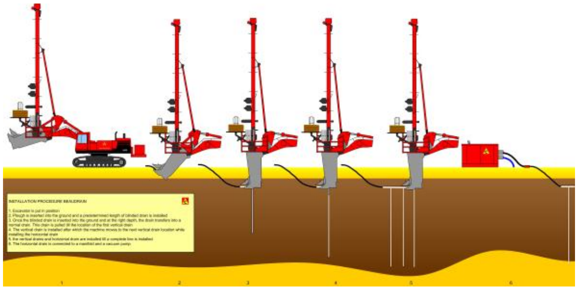

Figure 6. Work method vacuum system

5 EXECUTION

The very low strength of the peat caused major problems for the main contractor to deliver a 1 meter thick working platform. At some locations their heavy, fully loaded, equipment and method of placement led to major squeezing of the peat from underneath the platform, see Figure 7. Both the instability and other observations made, led to installation concerns for the vacuum system as the horizontal drain is required to be installed below the water table inside the soft compressible material. A maximum thickness of 2 meters is therefore allowed as working platform thickness. After consultation with the main contractor the quality of platform was improved considerably.

Additional site investigation using CPT testing and an electromagnetic survey, see Figure 8, confirmed the concern and showed that large sections of the working platform were thicker than allowable.

For these areas a design change was required. This design change also incorporated the change in construction time. Due to legal issues around the contract of the main contractor, the start of the execution of the work was delayed. The contract of the bridge was awarded with a fixed date for the closure of the very busy Amsterdam-Rhine channel and placement of the bridge. This meant that only eight months were available to consolidate the high eastern section of the embankment.

Figure 7. Squeezing of the peat under the placement of the sand

Figure 8. EM survey

In the updated design the drain spacing and fill height was adjusted to fit the time schedule. Sections with a deviating thickness of the platform were redesigned. Both a variation to the vacuum system, with each single drain having a blind section crossing the permeable layer and a connection to a vacuum pump(called BeauDrain-S) and vertical drains, with a 0.85m triangular grid spacing without vacuum pressure, were used.

The new layout of the methods, used in the design, is shown in Figure 9. In yellow the BeauDrain-S sections are visible and in red the dense 0.85m triangular spacing PVD grid section. In orange also PVD, but at this location, mapped using CPT testing, the extension of the soil replacement of the adjacent highway was detected.

The vacuum system was redesigned such that no connection was created between the vacuum system and the sand body of the highway. Vertical drains were installed in this transition zone.

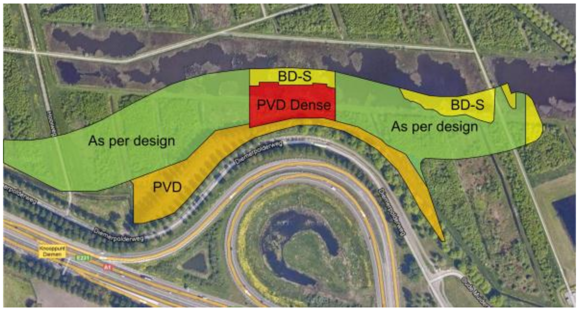

Figure 9. Final design of used ground improvement methods

The installation of the different systems took place with multiple machines between 28-06-2011 and 03-08-2011. Figure 10 shows the installation of the vertical drains and in the background the two vacuum drainage installation machines.

Figure 10. Installation of the vertical drains

During the summer holiday period, no sand was transported to the site over a period of four weeks. This led to a delay in the placement of the first lift on top of the working platform and a delay in the consolidation process. This lift was in place at 22-09-2011 on the complete area after which a fast lifting schedule was used. During weekly meetings between the main contractor, the engineer of the client and the specialists of Cofra, the filling rate, which was typically between 0.5m and 0.75m a week, was evaluated and optimized using up to date monitoring data. The final lift was placed seven months later in April 2012. The pumps were disconnected in June 2012.

6 MONITORING EQUIPMENT

During the consolidation and embankment construction different monitoring systems were in place. The settlement was recorded once a week using 56 settlement plates. During each measurement both the height of the top of the plate as well as the height of the embankment was measured. The latter was done to have actual data on the surface level and fixed information about the progress of the filling. Pore pressures were registered using nine Piezometers distributed over the surface. The lateral movement was registered using eight inclinometers. They were installed at critical locations, mainly next to the swamp area, located just north of the embankment.

7 MONITORING RESULTS

The settlement was measured during the surcharging period. Figure 11 presents the measured final settlements with values up to 4.0m as well as the volume reductions with values between 40 and 60%.

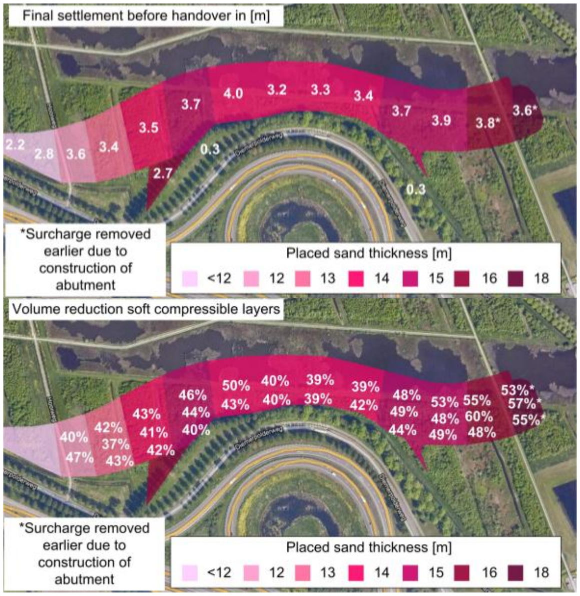

Figure 11. Measured settlements, top image, and compression rates bottom image

During the consolidation period, settlement fits were made using the HED-SET model. During a fit, the theoretical parameters are, within the natural boundaries, adjusted such that the theoretical line is located on top of the measured settlement in order to predict the future behavior and calculate the residual settlement. Two examples of the fits are given in Figure 12 and Figure 13.

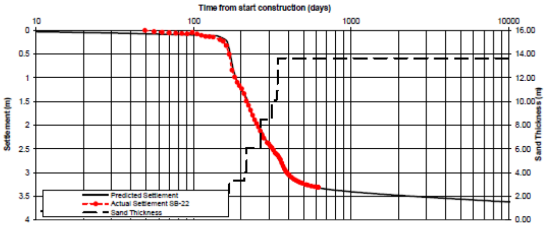

Figure 12. Settlement fit for the 14m thick sand body.

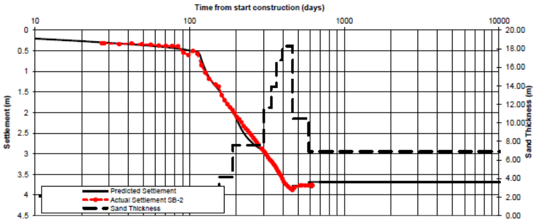

Figure 13. Settlement fit for the bridge abutment, where a large excavation took place to drive the piles for the bridge.

The large reduction in volume influenced the correlation of the measured settlement data with the theoretically calculated settlements. In this case the primary consolidation parameters were required to be reduced to incorporate the effects of the large strain and natural deviation from the linear behavior at these strain values. Due to this required reduction, a sensitivity analysis was performed on the other parameters, like the c_α creep factor, to determine the upper boundary of the residual settlement after construction.

The fits show that the factors used for the vertical drain areas coincide with the vacuum areas. This means the soil was modelled correctly and the vacuum pressure has worked well with the assumed pressure drop. If this would have not corresponded, there would be a deviation in the factors.

During the work the 23 pumps worked well with an average vacuum pressure over time and all the pumps of 78kPa.

The inclinometers were used to monitor the surcharge schedule. It was clearly visible in the measurements that the lifting schedule was highly optimal with sometimes deflections after a 0.75m lift of 4 to 5cm and during lifts of 0.5m in the order of 1 to 2cm

The pore pressure measurements were indicatively used, because it was noted that some piezometers were installed in the vicinity of a drain and reacting very rapidly on the filling schedule, while others were presumably affected by biological growth with strange deviations in the measured values.

8 CONCLUSION

The southern embankment of the eastern access route to IJburg was successfully constructed within the given boundary conditions with the help of a vacuum system. A redesign using various consolidation systems was required during the installation of the system. This was caused by a large variation in the thickness of the working platform. During the consolidation period an average volume reduction between 40 and 60% was achieved with absolute settlements up to 4 meters. Due to the close cooperation between all parties it was possible to use a fast lifting schedule of 0.5 to 0.75m of sand a week on the very soft subsoil.

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